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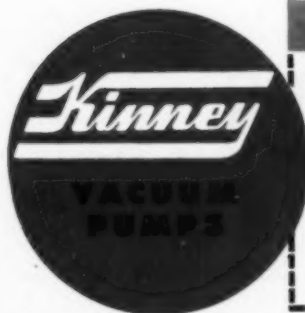
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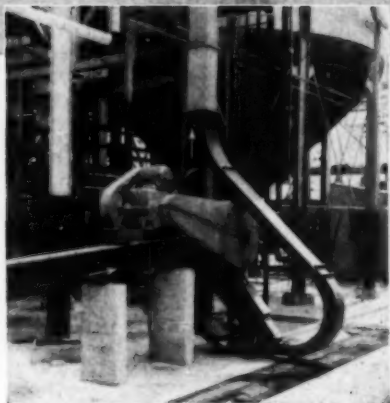
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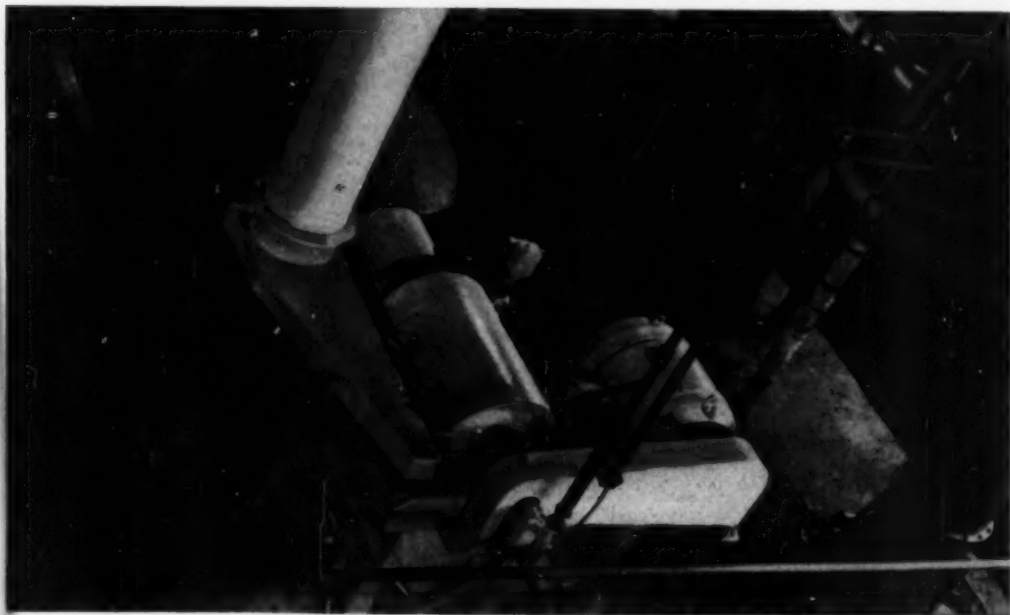
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TABLE No. 1—RESISTIVITIES

TYPICAL SERVICE CONDITIONS		% by Wt.	PH Value	PFAUDLER GLASS LININGS				OTHER MATERIALS												
				43	54	48	57	Nickel	Monel	Inconel	Aluminum	Copper	Dur-chlor	Hastelloy A,B,C&D	Karbate No. 1	Haveg	Lead	Rubber	304 Stain-less	316 Stain-less	347 Stain-less
HCl	Hydrochloric Acid	Conc. 35.0%—60° lbs.		R°	R*	NR	NR	NR	NR	NR	NR	NR	R†		R°	R	NR	—	NR	NR	NR
HCl	Hydrochloric Acid	N 3.50%	0.1	R°	R*	NR	NR	R	R	NR	NR	NR	R†		R°	R	NR	R	NR	NR	NR
HCl	Hydrochloric Acid	N/10 0.30%	1.0	R°	R*	NR	NR	R	R	R	NR	NR	R†		R°	R	NR	R	NR	NR	NR
HCl	Hydrochloric Acid	N/100 0.036%	2.0	R°	R*	NR	NR	R	R	R	NR	NR	R†		R°	R	NR	R	NR	NR	NR
H₂SO₄	Sulphuric Acid	Conc. 77.0%—60° lbs.		R°	R*	NR	NR	NR	R	NR	NR	NR	R**		R°	NR	R	—	NR	R	NR
H₂SO₄	Sulphuric Acid	N 4.75%	0.5	R°	R*	NR	NR	R	R	R	NR	R	R**		R°	R	R	R	NR	R	NR
H₂SO₄	Sulphuric Acid	N/10 0.49%	1.2	R°	R*	NR	NR	R	R	R	NR	R	R**		R	R	R	R	R	R*	R
H₂SO₄	Sulphuric Acid	N/100 0.049%	2.1	R°	R*	NR	NR	R	R	R	NR	R	R**		R	R	R	R	R	R*	R
HNO₃	Nitric Acid	Conc. 68.0%—60° lbs.	0.00	R°	R*	NR	NR	NR	NR	NR	R	NR	R**		NR	NR	NR	—	R*	R*	R*
HNO₃	Nitric Acid	N 6.30%	1.0	R°	R*	NR	NR	NR	NR	R	R	NR	R**		NR	NR	NR	—	R*	R*	R*
HNO₃	Nitric Acid	N/10 .63%	2.0	R°	R*	NR	NR	NR	NR	R	R	NR	R**		NR	NR	NR	—	R*	R*	R*
H₃PO₄	Phosphoric Acid	N 3.20%	2.0	R°	R*	R	NR	R	R*	R	NR	R	R**		R	R	R	R	—	—	—
H₃PO₄	Phosphoric Acid	N/10 0.32%	1.5	R°	R*	R	NR	R	R*	R	NR	R	R**		R	R	R	R	—	—	—
CH₃COOH	Acetic Acid	N 3.00%	2.4	R°	R*	R	NR	R	R	R	R	R	R**		R*	R	NR	R	R*	R*	R*
CH₃COOH	Acetic Acid	N/10 0.30%	2.9	R°	R*	R	R	R*	R*	R*	R	R	R**		R*	R	NR	R	R*	R*	R*
CH₃COOH	Acetic Acid	N/100 0.060%	3.4	R°	R*	R*2	R	R*	R*	R*	R	R	R**		R*	R	NR	R	R*	R*	R*
C₄H₆(OH)₂(COOH)₂	Tartaric Acid	N/10 0.75%	2.2	R°	R*	R*2	R	R*	R*	R*	NR	R	R**		R*	R	—		R*	R*	R*
COOHCH₂CH(OH)COOH	Malic Acid	N/10 0.67%	2.2	R°	R*	R*2	R	R*	R*	R*	NR	R	R**			R	—		R*	R*	R*
C₃H₄(OH)(COOH)₃·H₂O	Citric Acid	N/10 0.60%	2.2	R°	R*	R*2	R	R*	R*	R*	NR	R	R**		R*	R	—		R*	R*	R*
CH₃CHOHCOOH	Lactic Acid	N/10 0.90%	2.4	R°	R*	R*2	R	R*	R*	R*	NR	R	R**		R*	R	—		R*	R*	R*
CrO₃	Chromic Acid	50.0%		R°	—	—	—	NR	NR	—	NR	NR	R***		NR	NR	R	—	NR	NR	NR
NaHCO₃	Sod. Bicarbonate	N/10 0.84%	8.4	R	R	R	R	R*	R*	R*	NR	NR	R***		—	R	R	—	R*	R*	R
Na₂CO₃	Sod. Carbonate	N/10 0.53%	11.6	R	R	R	R	R*	R*	R*	NR	NR	NR		—	R	R	—	R*	R*	R
NH₄OH	Am. Hydroxide	N/10 0.35%	11.1	R	R	R	R	R*	R*	R*	NR	NR	NR		R	R	R	—	R*	R*	R*
NaOH	Sod. Hydroxide	N/10 0.40%	13.0	NR	NR	NR	NR	R*	R	NR	NR	NR	NR		—	R	NR	—	R*	R*	R
KOH	Pot. Hydroxide	N/10 0.56%	13.0	NR	NR	NR	NR	R*	R*	NR	NR	NR	NR		—	R	NR	—	R*	R*	R
Na₃PO₄·12H₂O	Trisod. Phosphate	N/10 1.27%	12.0	NR	NR	NR	NR			NR	NR	NR	—				NR	—	—	—	—

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OPINION AND COMMENT

CONSIDER THE ANT

RECENTLY, in a tropical forest, I saw a procession of small green objects like little flags moving slowly in a long line across obstacles in a rough terrain. Closer inspection showed that they were ants, each carrying a section of green leaf several times larger than itself. These leaf-cutting ants denude whole trees to make an underground compost for the culture of a certain fungus on which they feed. Their system is highly refined for they know how to eliminate unwanted bacteria and strains of fungus unsuited to their use. Some ants even make slaves of other insects.

My thoughts turned to the proverbial industry of ants and to the nature of life in such a community. Its marvelous organization of which we have but slight understanding excites our wonder. It seems to be engineering in a high state of development, but viewed from the standpoint of the individual creature it is a routine from which he cannot deviate except at the immediate risk of his life.

The practice of chemical engineering develops processes by which matter undergoes changes under a rigid system of control which aims at the elimination of any deviation from optimum conditions of time, temperature, proportion of reactants, or other conditions which affect quality or cost. A high value is set upon the continuous automatic stream in which the desired changes take place without the risks of imperfections due to the inconsistent performance of a human operator. The perfection of organization achieved along these lines is marvelous but at some point control devices have to be serviced, furnaces relined, worn parts replaced. The mechanical concept of the process has not changed but a new element enters—the human being—whom we understand imperfectly though we know something of his limitations, his aspirations, and the sources of his enthusiasms.

It is too easy to assume that men are closely analogous to inanimate matter and that under rigid organization, such as that which exists in the community of ants, they should perform with equal constancy. Rigid authoritarian control may have produced the pyramids and probably wrecked the state which could not afford such luxury of unproductive effort. Since then new ideas are brewing and the word *freedom* represents a deep-seated human need. Our sense of community,

which is a higher level than that of insects or slave states, recognizes that each human being has a separate personality and the right to separate development of his powers. Respect for human beings, queer and erratic as we are, is inherent in our history and our laws. To guide the actions of human beings in a democracy we must affect the inner springs of action—not coerce people against their best conscience and most responsible judgment.

We who strive for a free world in which voluntary cooperation is the basic pattern of society will do well to ponder long and earnestly how far we can substitute the doctrine of authority to gain immediate ends without sacrificing the very goals of democracy for which we strive.

We may ask ourselves such questions as how far the military mind, indoctrinated with authority and trained to short-range objectives is suited to dealing with the problems of diplomacy or even of domestic questions of fundamental policy.

Democracy is more difficult than other forms of social organization. It will not be achieved by imitating ants or pyramid builders or even by assuming that it is a problem of engineering. Rather, it must come from convincing the great majority of humankind that it is desirable. As we look around the world from this viewpoint, we of this nation, have cause to be profoundly humble.

We have developed the techniques by which life could be made better for all. Health, nutrition, shelter, the lifting of the back-breaking load of human labor by electric power are within our grasp. Even the banishment of superstition and fear and the development of a sense of belonging to a world community could come if we would really work at it. But the cold fact has to be faced that we have put national power ahead of these things and other nations are afraid of us. Fear is our great enemy.

Ants with subhuman talents are perhaps too insensitive to be afraid. They perform in a tight system of organization almost like molecules but the spirit of man is different and requires a different pattern of thought. Even in this time of stress we need to keep our eye far down the road.

James G. Vail.

ENGINEERS

THEIR BACKGROUND, EDUCATION AND SELECTION

ARTHUR L. MILLER and PAUL C. MILLER

Miller Associates, Boston, Mass.

THE man who administers an engineering department realizes all too well the need for reliable methods for selecting not only engineers who are capable of doing their work as assigned, but also engineers who have initiative and can think for themselves either theoretically or creatively.

The young engineer wants to know where he is going and what he can do to make the most of his abilities. The fact that some young men develop into more capable engineers than others makes it vitally important that educators, administrators and young men alike know how this happens and why.

In this paper an examination is made of the answers to four questions: (1) Why do young people go into engineering? (2) What does engineering education do to foster the intellectual development of the engineer? (3) What kinds of abilities are sought in engineers? (4) What is the current status of methods for the selection of engineers?

Beginning with the first question: Why do young people go into engineering?—Actually some sorting takes place, but what kind of young men do go to engineering school.

First, some of them are young men whose scientific and engineering curiosity has been awakened at an early age. In doing the things that satisfy that curiosity, they are drawn into the scientific or engineering field as if by a magnet.

The working of the child's mind when scientific curiosity has been aroused can be illustrated by two outstanding cases. The first is from the experiences of Michael Pupin (2).

As a boy in his early teens, in his native Serbia, he joined other boys as herdsman watching cattle at night, keeping them out of the grain fields and protecting them from cattle rustlers. In describing his experiences he tells us that one of the arts of a herdsman was signalling through the ground by striking against wooden handles of knives stuck in the ground. The boys, lying down and pressing their ears close to the ground, had to estimate the direction and the distance of the origin of the sound. Practice made them quite expert at signalling, although none of the herdsmen could explain how this phenomenon worked. However, young Pupin meditated a great deal about the nature of sound and of light. Twenty-five years later, one of his important discoveries was based on the reflections which were started when his curiosity was challenged by his novel experiences at the herdsman's summer school. But this is just one example out of many of the actively pursued curiosity that made it almost inevitable that Michael Pupin should become a scientist.

The second illustration of the way the child's mind works when scientific curiosity has been aroused is chosen from outside the engineering field, but the principle is the same. It is the case of a boy who was isolated socially, economically and educationally on the western edge of our great plains—Hertzler of Kansas who as you know later became the "Horse and Buggy Doctor." Here is the way he tells his story:

At about the age of ten years my medical education began. . . . I secured a copy of Dr. Foote's 'Family Physician' which I read again and again. Though but a child, I learned the description of many diseases, notably diphtheria and the itch. When I learned what diseases someone in the neighborhood had or died of, I hastily read it up in my book.

In my twelfth year we studied Steel's 'Physiology' in the country school. I committed the book to memory almost word for word. Because of my spare physical build, I was able to identify most of the bones mentioned in the book. Here budded my skepticism of recorded medical opinion. This book stated that the capacity of the human stomach was three pints. I easily demonstrated that insofar as I was concerned, this was a gross underestimate. I was later able to harmonize this difference of opinion. The stomach of the deceased person is contracted and rigid and in this condition holds about three pints, but a boy's stomach is capable of expansion far beyond the capacity of a cadaveric stomach.

Later, he went through medical school and began to specialize in surgery. He reports:

My pal and I registered for a special course on the nose and throat with the distinguished Professor Janzen, just because we both had the idea that a surgeon should know the entire operative field. There were forty-six students registered, all specialists except my pal and me. The students operated in turn. Janzen had a special technique and in turn the specialists failed. We got a bright idea. We got a set of Janzen's instruments and bribed our way into the deadhouse and did tonsilectomies on the late deceased. We became expert after doing several hundred operations on the cadavers. When it came our turn to operate on the living, we went through the procedure without a hitch, using either hand, à la Janzen. After watching us perform, the Professor did a flipflop and yelled, 'Natural throat specialists.'

We did another trick. Operative courses on the mastoid were done on temporal bones which were removed during routine autopsies. By deft persuasion on the part of my pal, we acquired eighty-eight of these, just forty-four apiece. By practicing on these, we became so expert that we could expose the ridge that houses the facial nerve as it passes out in three minutes. We sprang this on Janzen too. He had another fit and urged us to accept assistantships with him. Of course, we were very modest about the whole thing (1).

A second group of young men, probably a great many, go to engineering school because they are caught up by the romance of engineering. A generation ago, the figure of Thomas A. Edison was silhouetted on the horizon and in the gaze of every American boy. Being so completely in the American

tradition of rising without benefit of formal education, it was easy for him to become an engineering idol and legend and to capture the imagination of a generation of American youth. At a more sophisticated level, the name of Steinmetz became legendary. There is a young man in Union College today who should normally have gone to Yale, majored in science and taken a doctorate in some special phase of science, but he went to Union because it is the college associated with the General Electric Co. and Steinmetz—the General Electric Co. because it was the company of Steinmetz.

Since the splitting of the atom, there is a complete galaxy of scientists in the firmament, first, second, third and lesser magnitudes. The youth can't even turn his back. The firmament lies before him in all directions.

A third group that goes to engineering school consists of young men who are intelligently motivated and guided towards the engineering field by their elders, parents, teachers, friends and guidance people.

In the fourth group there is that great intellectually unawakened mass who want the prestige of being college men, who feel that they must avoid being among the unemployed and who choose engineering for more or less nebulous and rationalized reasons, such as living in the engineering age.

As the American youth is brought to the entrance gates of the engineering college, the next question is: What does engineering education do to foster the *intellectual development* of the engineer? What is meant by intellectual development?

At a relatively simple level, human, mental or intellectual functioning often consists of not much more than the ability to memorize and then repeat back what one has memorized. It doesn't necessarily require any great comprehension of what one has memorized. Many people have survived four years of a liberal arts college on not much more than this.

At a somewhat higher level is the ability to memorize rules and formulae and to know when to apply them or how to substitute into them. Many young men have survived four years of engineering college without much more than this.

At a still higher level is the ability to understand the theories from which the rules and formulae have been derived and to think comfortably within the framework of these existing theories.

Beyond this is the level of ability found in the man who, having made a conjecture, can establish a working hypothesis and begin experimentation. As

his evidence accumulates, he broods over it, trying to fit it into his hypothetical structure; and as his evidence begins to support his hypothesis, theory begins to take form and hypothesis gives way to theory.

Each of these levels of ability represents a stage of intellectual development. By intellectual development, then, we mean the process of growing intellectually so that one gradually acquires the ability to function effectively at each of these successive levels.

The cloud that hangs over technical education, both engineering and business, is that it is possible to go through college and make high marks by using only rules and formulae. Too often engineering students have been prepared for college by being drilled in the application of rules and formulae of science and engineering rather than having been taught how to do some first-hand thinking along with the rules and formulae. Once in college, there is often no personal experience with conjecture, the making of hypotheses or theorizing, and only a memory contact with principles and laws for the purposes of passing quizzes and term examinations or quoting them in a "slide-rule level" paper.

As an example of what can happen, there is the case of Mr. M——— who was tested recently during his 15th year out of college. He was a member of Sigma Xi; his intellectual endowment was the answer to an engineer's prayer. He had everything. At work he was doing a good job in an area of engineering design. Tell him what was wanted and he would do it. He *should* have been a top man among big men, but he wasn't. He had not experienced the mental development that was necessary in order to make first-rate use of his tremendous innate ability. Although he was a member of the scientific honor society, he had read *Time* magazine and the *Reader's Digest* for 15 years. Nothing more. He had used the techniques provided by the engineering school and had done his work as assigned.

Now all engineers are not going to be Pupins or all doctors Hertzlers, but the point is that there is a crying need for more engineers whose curiosity is not only stimulated but who have learned how to do independent thinking—who can think beyond the limits of intellectually prefabricated areas. The mind —engineering, scientific or otherwise— does not grow merely as a result of being exposed to perfect tools in the engineering laboratories and to textbook assignments that require one to do nothing more than memorize and apply rules and formulae.

In earlier days, a curse was hung on

the man with a theoretical mind by the business world, but this was the result of loose definitions and prejudice. What was meant was the impractical mind and the academic mind with limited practical experience. The difference between the mind of the theorist and the mind of the technologist shows up in actual practice. Here is an instance. In a certain company that uses chemical manufacturing processes, the policy is for the plants to call upon "central engineering" when something develops that is not readily corrected from general plant experience. A situation of this type came up. A young engineer was sent down to the plant from central engineering. Days went by and time began to weigh on the rule that if an engineer could stay on such a job without success, beyond a specified time, he would become permanently damaged in his standing within the department. He was recalled. A philosophic-minded engineer —a theorist—decided to go down. But before going down he collected the data, organized it, set up a theory as to what should happen and where in the chemical processes involved. He then went down to the plant, ran tests, made the corrections called for on the basis of chemical theory, and finished within less than three hours.

In dealing with equipment and mechanical processes the technologist is usually sufficient and may be even more effective than the theorist because of his sharp spatial perceptions. But when dealing with more obscure phenomena, good perceptions, the basic aptitudes, and the rules of the textbook are not enough.

It is obvious that not all students in engineering school end up with the same degree of intellectual development or the same degree of technical proficiency. The same thing is found when one looks at engineers who are many years removed from their college days. They range from slide-rule technicians up through creative engineers, theorists, and administrative engineers. These differences are attributed partly to each person's original intellectual endowment (his innate ability) and partly to the kind and quantity of motivation he had for developing his endowment to the greatest possible degree.

Experience indicates that the best intellectual development in engineers usually takes place in those cases where awakened scientific curiosity is followed by identification with a hero and the benefits of good guidance.

Those who have not experienced an awakening of their scientific curiosity and who have not been so stimulated are less likely to undergo good intellectual development because they are dependent too largely upon whether some teacher

tugs consistently and successfully at their curiosity and their hope for achievement.

The primary value of tests of vocational interest in the selection of engineers is at this point. They give some indication of whether a person has the motivation to make the best use of his innate abilities.

It has been noted that not all students in engineering school or men who have spent years as engineers end up with the same degree of intellectual development or the same degree of technical proficiency. Here is the challenge. If these differences among engineers do exist, can the different kinds and level of engineering aptitude or ability be discovered through the use of psychological tests, and can engineering administrators be selected through the use of psychological tests? The answer to both questions is yes. Not perfectly at present by any means, but highly profitably even at the present. With cooperation between engineers and research psychologists, the predictive value of tests can be made even more specific and even more specifically accurate.

In order to decide whether a given engineer can meet the requirements of a particular engineering job, the requirements must be known. In general, the requirements for various engineering jobs cover five areas:

1. The primary area is engineering aptitude—original innate endowment. Without this primary engineering equipment little gain will accrue from either training or experience.
2. The secondary area is engineering training, both formal and informal—in brief, how much of the abundance of recorded engineering knowledge and experience has the engineer assimilated and appropriated
3. A third area is that of intellectual development. This has been defined as the extent to which an engineer has gone beyond mere memory for established rules and is capable of thinking or creating in his own right.
4. A fourth area is that of engineering experience. What is the quality of the engineer's experience in both breadth and depth? What kind and quality of apprenticeship, both formally and informally, has he served
5. The fifth area is that of engineering administration. Does the engineer have the aptitude for organizing work, and for directing and coordinating other engineers in getting work done

The traditional method of assessing engineering ability has been for an employer to investigate these five areas as thoroughly as possible by a careful study of an individual's past experience. In the case of an engineer who is ten or more years out of engineering school, if the employer compiles accurate data about the engineer's past experience (high school, college and vocation-pro-

fession), and if he understands and interprets these data correctly, he should be able to predict what the engineer can do best and how well. Almost everyone is somewhat unhappy with that method; too many mistakes have been seen.

In actual practice the traditional method fails in two ways: (1) the employer seldom has the time to compile the information thoroughly and accurately, (2) few employers are adequately trained in comprehending and interpreting the information. Even if the traditional method were reasonably successful in selecting experienced engineers, it is inadequate for the task of guiding high school students into or away from engineering training and for selecting student engineers as they leave college and university because their past achievements often are too limited to be a safe basis for predicting their futures.

This brings us back to the challenge: Can engineering aptitude be discovered through the use of psychological tests, and can engineering administrators be selected through the use of psychological tests?

The answer is still yes. But in order to understand how tests can be applied to this problem it is helpful to chart out the intellectual functions used by the engineer in his work. They are as follows:

1. Manual intelligence or manual dexterity—that is, intelligent hands and fingers that can carry out the intentions of the mind.
2. Ability to perceive and to visualize spatial relationships.
3. Mathematical intelligence.
4. Ability to make abstractions from specific instances—to see what common factors are shared by separate instances, to see the general implications of a particular series of events.
5. Ability to operate within established theory—to understand established theory and to think effectively within its limits.
6. Ability to contemplate and to structuralize ideas in the absence of theory, and to work toward new theory. Sometimes people with this ability are referred to as having a philosophical or creative mind.
7. Ability to plan, coordinate, and direct the activities of other engineers.

These seven abilities represent the more important intellectual functions used by engineers in their work. Of course, not all engineers possess large amounts of all seven types of ability. However, it is important to recognize that not all engineering jobs require all seven abilities. Some jobs are well filled by a slide-rule technician; other jobs require a top-flight engineer. The important thing is not to send a boy on a man's errand, or even more wasteful, to send a man on a boy's errand.

What can psychological tests do to

select engineers who have the proper combination of these seven abilities to meet the requirements of the job for which they are being considered?

1. Tests of manual dexterity have been rather well established for about 20 years. Johnson O'Connor, who later established the Human Engineering Laboratories, developed two tests that have been rather effective for selecting persons with the dexterities to handle small tools and instruments and to do precision work. He did this while employed by the General Electric Co. during the 1920's. Since that time other tests have been developed that serve the same general purpose.

Manual dexterity is highly important for some technicians and for all others whose work requires precision of movement and delicacy of touch. It is highly important for the engineer (and scientist) who is his own technician and pattern maker or who makes his own mock-ups—who, in a word, is a man of all work.

However, it is felt that manual dexterity occupies so minor a place in the activity of the engineer of today that we discontinued giving such tests to engineers several years ago.

2. Ability to perceive and to visualize spatial relationships lies at the heart of the work of the mechanic, toolmaker, draftsman and practical engineer. Tests of spatial relationships have received considerable attention, especially in recent years, and are rather highly developed.

3. Tests of mathematical intelligence also have received much profitable attention and are available in a variety of forms depending upon whether speed of thinking or complexity of thinking is emphasized.

4. Philosophers in their studies of formal logic have dealt with such problems as making generalities from specific instances, and levels of abstraction in thinking for many, many years. Psychologists have used the syllogism in test construction for quite a few years. They have also developed tests of the ability to think at a conceptual level. However, many of these efforts have had limited practical value for the selection of engineers. It is only recently that practical tests of high level ability to think abstractly and to manipulate a problem within the area of established theory have been developed.

5. Tests of the philosophical or contemplative or creative mind are fairly well developed, although not at all widely used in the selection of engineers.

6. The task of selecting engineering administrators is simply one of selecting administrators from among engineers. Good administrators have good "feeling for others," are stable in their emotions but not rigid and inflexible; they are practical-minded, good thinkers when dealing with current nontechnical problems and have the imagination to get their ideas across. Tests have been used successfully for several years to select men with administrative ability.

Here are some cases selected from the experience of Miller Associates to show what can be and is being done by the

proper use of tests in selecting and placing engineers and also equipment design and development craftsmen:

A few years ago an experimental study was made of 21 men representing a cross section of a large equipment shop. All these men were at the craftsman level. Even though there were crack designers in the group there were no college-trained men among them. Each man's adjustment to his job, his fellow-workers, and his superiors was to be described, as well as the quality of performance that could be expected of him; his enterprise; and his leadership qualities. No interviews were permitted and no names were used; the men were given code numbers for the test experiment. It was a simple case of blind flying, drawing conclusions entirely from the test data. After the tests results were put together and discussed the three men responsible for the equipment department said: "These test results have told us what it has taken from five to ten years to learn from observation."

As a result of that same study, one able man who was deeply frustrated because he was head and shoulders above his two bosses in ability was salvaged, given some guidance in adjustment and has been running a profitable equipment shop for five years. His shop has done many things that the head of the old shop said could not be done.

Poor personal adjustment often hides real engineering promise. Some years ago a young engineer who had a doctorate in physics was tested. At that time his standing in the eyes of most of top management was just above the level of disgrace because of his poor attitude and because he scorned the idea of "selling" his results. Tests showed that he had an excellent theoretical and creative mind, and the potential for administrative work if he would change his attitudes and his feeling toward some people. Since that time many of his attitudes have changed, he has developed and administered a fine research department, and he is now among the real "top brass" in his company.

In another company an experimental study of five research men was made, all with well-established performance records. In the words of management the group consisted of "one technologist, two fine research men, one scholar and one genius." Of course there was no sure idea what was meant by a "genius" or how to distinguish a technologist from a research man and nobody was told which man was which. The question was, could they be sorted out. They could.

It was done by describing how well

each man could meet the requirements of various kinds of work.

The tests showed the following results:

The *genius*, in addition to having a mind well stored with scientific knowledge and having high ratings in comprehension of mechanical relationships and in scientific aptitude, had what was classified as a well-developed creative mind with fine capacity for making both a theoretical and creative approach to a problem.

The *scholar* had high ratings in comprehension of mechanical relationships and in scientific aptitude, a mind well stored with scientific knowledge, and a scholarly vocabulary. In addition, he had exceptional ability to utilize established theory, and fair creative ability.

The two *research* men had high ratings in comprehension of mechanical relationships, and minds almost as well stocked with scientific knowledge as the genius and the scholar, but they were almost totally lacking in the capacity for creative and philosophic thinking.

The *technologist* was equal to the scholar in his potential for creative and philosophic thinking and almost equally well informed. He had only slightly lower ratings in comprehension of mechanical relationships and in scientific aptitude. However, he was easily baffled and confused by unfamiliar problems and was not able to use his ability with effectiveness except where he was on familiar ground.

Of the five men, only the technologist had had more than four years of college. He had received the doctorate from a first-class university.

The abilities of many good engineers are wasted because they are put on the wrong kind of job, because they have the wrong kind of boss, or because they are given the wrong kind of responsibility. As an illustration, a few years ago an instructor in chemistry wanted to transfer to industry for chemical research. After testing him, Miller Associates suggested that he would pay off if given the right kind of working conditions and the right kind of supervision, but only if these conditions were met. He needed to work under stable conditions where he would know what he was expected to do technically, where he could do it alone, and where he would not feel under pressure. He needed a supervisor who would be friendly, who would give him the assignments, provide the equipment, and see that he was protected against pressure from others. These conditions were met and he was given a major assignment. In less than a year he came through on the project with a development that would save many thousands of dollars a year.

At this point, certain persons, without conferring with the people in the original agreement, started to urge this research man to supervise putting the new methods into production. The assignment frightened him and he was

ready to quit his job. However, the situation was saved when a production engineer was assigned to do the job using the research man as a consultant, and all ended well.

These illustrations demonstrate that present-day psychological testing, when carefully done, can make a valuable contribution to the engineering field.

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(Presented at Boston (Mass.) Meeting.

LETTER TO THE EDITOR

Notation for Large and Small Numbers

Sir:

Writing in your January issue (p. 38) J. W. Clegg puts his finger on a real need, namely, for some system of abbreviated numerical notation which will facilitate the placing of the decimal point in slide-rule calculations.

For a good many years I have used a power system of my own which is identical in principle with Mr. Clegg's but somewhat differently written. Applying it to examples from Mr. Clegg's letter:

$$0.000672 = 6.72 \times 10^{-4} \quad \text{written} \quad 6.72\bar{4}$$

$$4800 = 4.8 \times 10^{3} \quad \text{written} \quad 4.8\underline{3}$$

These figures may be read "six point seven two *bar* four" and "four point eight *step* three," respectively. It is possible that with this notation the powers are more easily picked out by eye than when they are inserted over the decimal point. Also the figures are slightly more compact.

I generally use a dot for multiplication instead of brackets. There is no confusion with the decimal point provided individual factors are spaced well apart (theoretically the decimal point should be above the writing line, the multiplication point on it). The full compound fraction quoted by Mr. Clegg would then appear as:

$$\frac{1.049 \; . \; 4.80\underline{2}}{1.2\bar{1} \; . \; 3.60\underline{2} \; . \; 6.00\underline{3} \; . \; 9.787\bar{1} \; . \; 6.72\bar{1}}$$

R. Edgeworth Johnstone

London, England
Feb. 7, 1951

SEPARATION OF GAS MIXTURES BY MASS DIFFUSION

PART II

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Introduction

PART I described equipment which might be used to separate gas mixtures by either the column or the stage type of mass diffusion process, and derived the theory of the separation of isotopic mixtures by a cascade of mass diffusion columns. Part II continues with a discussion of the separation of isotopic mixtures by a cascade of mass diffusion stages and then treats the extraction of hydrogen from gas mixtures by each type of mass diffusion.

7. Separation of Isotopes by Cascade of Mass Diffusion Stages

7.1 Cascade of Mass Diffusion Stages. Figure 8 illustrates the schematic flow through a cascade of mass diffusion stages such as would be used in separating isotopes. The heavy stream entering each stage consists of downflow from the next higher stage and upflow from the next lower stage, from which most of the separating agent has been removed by the condenser; the light stream entering each stage consists of pure separating agent flowing at the rate J.

Such a cascade for isotope separation is characterized by:

1. Small differences in composition between the light and heavy streams of a stage.
2. A large reflux ratio, V/B, so that the upflow and downflow rates differ percentage-wise by only a small amount.
3. Adjacent stages either identical in size, or differing percentage-wise by only a small amount.
4. The largest stages at the feed point and smallest stages at the product ends.

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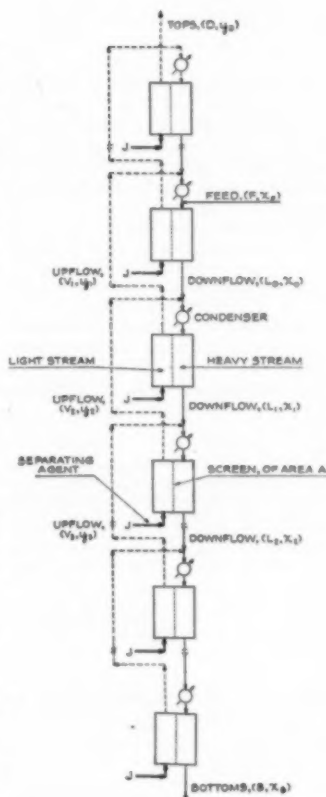
Fig. 8. Cascade of mass diffusion stages.

Molal flow rates (V, L, F, D, B) and mole fractions of light component (y, x, x_F, y_D, x_B) are on separating agent-free basis.

The most important properties of a stage are defined below:

1. *Stage enrichment factor*, ψ:

$$\psi = \frac{y - x}{x(1 - x)} \qquad (77)$$

where y and x are the mole fractions of light component in the light and heavy streams leaving a stage, on a separating agent free basis. ψ is small relative to unity.

2. *Ratio of screen area to upflow rate, a:*

$$a = A/V \qquad (78)$$

3. *Ratio of separating agent feed rate to upflow rate, j:*

$$j = J/V \qquad (79)$$

The following discussion shows how the total number of stages in a cascade, and the total area and total consumption of separating agent, depend on these stage properties, at the optimum interstage flow rate.

By a light component material balance at the stage below the feed:

$$L_0 x_0 = V_1 y_1 + B x_B \qquad (80)$$

y_1 may be replaced by its value in terms of x_1 and the stage enrichment factor from (77):

$$L_0 x_0 = V_1[x_1 + \psi x_1(1 - x_1)] + B x_B \qquad (81)$$

But $L_0 = V_1 + B$, so that

$$x_0 - x_1 = \psi x_1(1 - x_1) - \frac{B}{V_1}(x_0 - x_B) \qquad (82)$$

The optimum value of V_1 will be the one which makes $(x_0 - x_1)/V_1$ a maximum, (i.e., the greatest increase in concentration for the least amount of upflow), which is:

$$(V_1)_{opt.} = \frac{2B(x_0 - x_B)}{\psi x_1(1 - x_1)} \qquad (83)$$

It may be noted that this optimum flow rate results in zero composition difference between the upflow and downflow streams which are mixed to provide stage feed; that is

$$y_2 = x_0 \qquad (84)$$

A cascade in which this is true is known as an *ideal cascade*.

At the optimum upflow rate, it is noted from (82) that

$$(x_0 - x_1)_{opt.} = \frac{\psi}{2} x_1(1 - x_1) \qquad (85)$$

Since x_0 and x_1 are nearly equal, this may be replaced by a differential equation in n, the number of stages:

$$\frac{dx}{dn} = \frac{\psi}{2} x(1 - x) \qquad (86)$$

The total number of stages between the bottom and top ends of the cascade, N, is obtained by integrating (86) between x_B and y_D:

$$N_{opt.} = \frac{2}{\psi} \ln\left[\frac{y_D(1 - x_B)}{(1 - y_D)x_B}\right] \qquad (87)$$

This is just twice the minimum number of stages needed at total reflux.

The total interstage flow rate in the stripping section under these optimum conditions, $(V_B)_{min.}$ is given by:

$$(V_B)_{min.} = \sum (V_i)_{min.}$$
$$= B \sum \frac{2(x_i - x_B)}{\psi x_i(1 - x_i)} \qquad (88)$$

The sum may be replaced by an integral:

$$(V_B)_{min.} = B \int_{x_B}^{x_F} \frac{2(x - x_B)}{\psi x(1 - x)} \frac{dn}{dx} dx \qquad (89)$$

Since dn/dx is given by (86),

$$(V_B)_{min.} = \frac{4B}{\psi^2} \int_{x_B}^{x_F} \frac{x - x_B}{x^2(1 - x)^2} dx$$
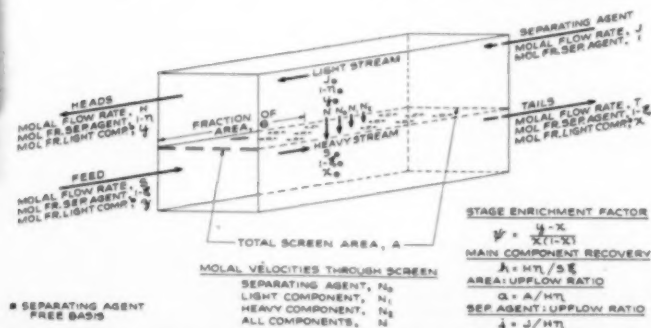
$$= \frac{4B}{\psi^2} \pi(x_F, x_B) \qquad (90)$$

where $\pi(x_F, x_B)$ is the separation potential, defined by (57). Similarly, the total flow rate in both stripping and rectifying sections is:

$$V_{min.} = \frac{4}{\psi^2}[B\pi(x_F, x_B) + D\pi(x_F, y_D)] \qquad (91)$$

If uniform conditions are used in all stages of the cascade, the total screen area for rectifying and stripping sections is

$$A_{min.} = aV_{min.} =$$
$$\frac{4a}{\psi^2}[B\pi(x_F, x_B) + D\pi(x_F, y_D)] \qquad (92)$$

and the total separating agent consumption is

$$J_{min.} = \frac{4j}{\psi^2}[B\pi(x_F, x_B) + D\pi(x_F, y_D)] \qquad (93)$$

7.2 *Stage Characteristics.* The stage properties ψ, a and j are functions of the diffusional properties of the mixture, D_o, D_{12} and γ, which have been defined in Section 5, and of four independent variables characterizing the conditions under which the stage is operated. Figure 9 illustrates flow through a countercurrent mass diffusion stage and defines the principal variables which will be used to describe its performance and derive its performance equations.

Derivation of equations for ψ, a and j for the case of equal diffusion coefficients $(D_o = D_{12})$ is given in 7.5. Here the results are recapitulated when the four independent variables are taken as:

1. h, the recovery of the stage, defined as the ratio of heads to stage feed, on a separating agent-free basis. In terms of the variables of Figure 8, $h = V/(V + L)$. Since the upflow and downflow rates are substantially equal, in the cascade shown in Figure 8, $h = \frac{1}{2}$. In terms of the var-

iables of Figure 9, $h = H\eta/S\xi$. By material balance, it can be shown that

$$h = \frac{z - x}{y - x}$$

2. ξ, mole fraction of main components in stage feed.

3. η, mole fraction of main components in heads fraction leaving stage.

4. U, reduced molal velocity through the screen, $NZ/D_o\rho$. In terms of these variables:

$$\psi = \frac{\gamma U(1 - \eta/\xi)}{1 - e^{-U}} \frac{\ln[(1 - \eta/\xi)/(1 - h)]}{h - \eta/\xi} \qquad (94)$$

$$a = \left[\frac{Z}{D_o\rho U\xi h}\right]\frac{\left[\frac{1 - \eta/\xi}{1 - h}\right]^{e^U - 1} - 1}{1 - \eta/\xi h\left[\frac{1 - \eta/\xi}{1 - h}\right]^{e^U - 1}} \qquad (95)$$

$$j = \left[\frac{1}{\xi h}\right]\frac{\frac{h\xi}{\eta} - 1}{1 - \frac{\eta}{h\xi}\left[\frac{1 - \eta/\xi}{1 - h}\right]^{e^U - 1}} \qquad (96)$$

These equations may be put into a form permitting graphical representation by introducing the variables:

$$q = aD_o\rho\xi h/Z \qquad (97)$$

and

$$p = j\xi h \qquad (98)$$

Since $h = H\eta/S\xi$ and $j = J/H\eta$, it is seen that

$$q = D_o\rho A/SZ \qquad (99)$$

a dimensionless ratio of screen area to stage feed, and

$$p = J/S \qquad (100)$$

the ratio of separating agent to stage feed.

With these substitutions in (94), (95) and (96), and by letting $h = \frac{1}{2}$, the stage performance equations become:

$$\psi = \frac{\gamma U}{1 - e^{-U}} \frac{2(1 - \eta/\xi)}{1 - 2\eta/\xi} \ln 2(1 - \eta/\xi) \qquad (101)$$

$$q = \frac{[2(1 - \eta/\xi)]^{e^U - 1} - 1}{1 - \frac{2\eta}{\xi}[2(1 - \eta/\xi)]^{e^U - 1}} \frac{1}{U} \qquad (102)$$

$$p = \frac{\frac{\xi}{2\eta} - 1}{1 - \frac{2\eta}{\xi}[2(1 - \eta/\xi)]^{e^U - 1}} \qquad (103)$$

In designing a mass diffusion stage, one will ordinarily be more interested

Fig. 9. Nomenclature for mass diffusion stage for isotope separation.

in the variables p and q, which are directly related to the screen area and separating agent consumption, than in U, the reduced molal velocity through the screen, or in η/ξ. Accordingly, U and η/ξ have been eliminated numerically from (101), (102) and (103). In Figure 10,[‡] contours of the relative enrichment factor, ψ/γ, are plotted as a function of p and q. This chart shows that (1) for each value of p there is an optimum value of q, at which ψ is a maximum, and (2) as p is increased, ψ increases.

If the sole design objective were to reduce the number of stages, which are inversely proportional to ψ, each stage would be designed with a high value of p, and the associated optimum value of q. But since it is also desirable to minimize the total consumption of separating agent and the total amount of screen area, p and q should not be increased indefinitely. In fact, the minimum screen area for the entire cascade is obtained by choosing p and q to minimize $2q/(\psi/\gamma)^2$, since it can be shown from (92) and (97) that the total screen area in an ideal cascade is given by

$$A_{\min.} = \frac{4}{\gamma^2 D_o p} \frac{2q}{\xi(\psi/\gamma)^2} [B\pi(x_F, x_B) + D\pi(x_F, y_D)]Z \quad (104)$$

Similarly, the minimum separating agent consumption for the entire cascade is obtained by choosing p and q to minimize $2p/(\psi/\gamma)^2$, since it can be seen from (93) and (98) that the total separating agent consumption in an ideal cascade is given by

$$J_{\min.} = \frac{4}{\gamma^2} \frac{2p}{\xi(\psi/\gamma)^2} [B\pi(x_F, x_B) + D\pi(x_F, y_D)] \quad (105)$$

Both screen area and separating agent consumption are inversely proportional to ξ, and are smallest at $\xi = 1.0$.

Figure 11[‡] is a plot of contours of the relative separating agent consumption, $2p/(\psi/\gamma)^2$, (dashed lines) and the relative screen area, $2q/(\psi/\gamma)^2$, (full lines) as functions of p and q. Separating agent consumption is a minimum at $p = 1.0$, $q = 1.0$. On the other hand, screen area is a minimum at $p = \infty$, $q = 0.82$. Thus, in the stage type of mass diffusion, as in the column, it is impossible to pick operating conditions which simultaneously minimize screen area and separating agent consumption. Conditions which provide a practical compromise between minimizing screen area and minimizing separating agent consumption will occur where contours of the relative screen area and relative separating agent consumption are tangent. This occurs close to $q = 1.0$. The value of p representing a practical optimum will depend on the relative costs of screen and separating agent. An optimum

value of p around 1.9 is typical.

Values of p and q at which $U = 0$ are shown by the dotted line of Figure 11. Since contours of $2\psi/p^2$ and $2\psi/q^2$ are nearly tangent along this line, the condition $U = 0$ is also close to the practical optimum. At $U = 0$, simple equations may be given for p, ψ and a. From (103) it is seen that

$$\xi/\eta = 2p \quad (106)$$

When this value of ξ/η and $U = 0$ are substituted in (101), there results:

$$\psi = \frac{\gamma(2 - 1/p) \, ln \, (2 - 1/p)}{1 - 1/p} \quad (107)$$

Similarly, when this value of ξ/η and $h = \frac{1}{2}$ are substituted in (95) and U is allowed to approach 0, there results:

$$a = \frac{2Z}{D_o p \xi} \frac{ln \, (2 - 1/p)}{1 - 1/p} \quad (108)$$

To obtain the maximum value of ξ, it will be desirable to use the lowest practicable temperature in condensing separating agent from the combined upflow and downflow before they are fed to the stage. When steam is used as separating agent at atmospheric pressure, a value of ξ around 0.9 is attainable without refrigeration.

7.3 Comparison of Stage with Column. The close analogy between Equation (104), giving the total screen area in a cascade of mass diffusion stages and Equation (58) giving the total screen area in a mass diffusion column will be noted. These equations differ only in their second factors, the relative screen area. A similar close analogy exists between Equation (105) and (60) for the total separating agent consumption in stage and column.

Table 3 compares numerical values for the relative screen area and relative separating agent consumption in the column and stage types of mass diffusion at conditions which lead to minimum screen area, minimum separating agent and the practical optimum. The stage type of process requires more screen area and more separating agent than the column type. This is primarily a consequence of the impossibility of maintaining optimum concentrations on each side of the screen throughout a mass diffusion stage, with conditions changing from point to point.

7.4 Production of $C^{13}H_4$ by Cascade of Mass Diffusion Stages. To illustrate this discussion of mass diffusion stages, the main features of a cascade of stages to produce 100 g./day of carbon-13, 90% pure, in 10% yield by mass diffusion into steam are given in Table 4. Compositions and flow rates of bottoms, feed, and tops have been given previously in Section 6.3. Diffusion coefficients have been given in Table 1. It is again assumed that $Z = 0.111$. The practical optimum stage conditions listed in the last column of Table 3 are used.

Comparison with Table 2 shows that this cascade of mass diffusion stages needs 63% more area and consumes 41% more steam than a cascade of mass diffusion columns. These disadvantages of the stage type of process are partially offset by its simpler equipment design.

7.5 Derivation of Stage Characteristic Equations. Equations (94), (95) and (96) which have been used to describe the characteristics of a countercurrent mass diffusion stage treating a close-cut mixture, such as an isotropic mixture are next derived. It is assumed that the coefficient of diffusion of the substances being separated, D_{13}, equals the arithmetic mean of their diffusion coefficients into separating agent, D_o.

Flow through a countercurrent, flat plate, mass diffusion stage is illustrated in Figure 9, which gives the terminology and notation to be used in deriving these equations. The feed enters one end of the heavy stream side of the stage at flow rate S. It contains $1 - \xi$ mole fraction of separating agent and z mole fraction of light component, on a separating-agent-free basis. In its flow through the stage, the heavy stream picks up separating agent flowing through the screen and gives up light and heavy components which diffuse through the screen, against the separating agent, the light component diffusing at a faster rate than the heavy. It finally emerges at the far end of the stage as the tails fraction, at a flow rate T, containing $1 - \xi_T$ mole fraction separating agent and x mole fraction light component.[†]

Pure separating agent enters the tails end of the light stream side of the stage at a rate J. In its flow through the stage, the light stream gives up separating agent to the heavy stream, and picks up light and heavy components by diffusion. It leaves the stage as the heads fraction, at a flow rate H, containing $1 - \eta$ mole fraction separating agent and y mole fraction light component.[†] Since the diffusion coefficient of light component is greater than heavy, $y > z > x$.

$(D_e = D_{12})$

Condition Type of Process	Minimum Screen Area		Minimum Separating Agent		Practical Optimum	
	Column	Stage	Column	Stage	Column	Stage
p, Separating agent: feed ratio	.....	∞	....	1.0	....	1.9
q, Screen area: feed ratio	.....	0.929	....	1.0	....	1.0
ξ, Mole fraction main components in feed †	1.0	1.0	1.0	1.0	0.9	0.9
η, Mole fraction main components in heads ‡	0.067	0.000	0.23	0.50	0.10	0.257
U, Reduced molal velocity through screen	2.70	0.20	1.47	0.00	2.20	0.15
Relative screen area	0.71	0.71	1.07	2.0	0.885	1.37
Relative separating agent consumption	1.91		1.55	2.0	1.835	2.60

† In heavy stream, for column type.
‡ In light stream, for column type.

When the heavy stream has flowed past θ fraction of the screen area, its flow rate is S_θ, its mole fraction of separating agent has been increased to $1 - \xi_\theta$ and its mole fraction of light component† has been reduced to x_θ. At the same point on the other side of the screen, the flow rate of the light stream is J_θ, the mole fraction of separating agent has been reduced to $1 - \eta_\theta$ and the mole fraction of light component † has been increased to y_θ.

At this point, the molal velocities of separating agent, light and heavy components through the screen are N_0, N_1 and N_2 respectively. These molal velocities depend on the mole fractions at this point, the diffusion coefficients, the effective diffusion length of the stage, Z, and the total molal velocity through the screen, as summarized by Equations (28) and (37). The total molal velocity through the screen is determined by the screen permeability and the pressure drop across the screen.

First, material balance equations will be written for the mixture as a whole, from which the flow rates S_θ and J_θ are obtained as functions of θ. Second, material balance equations will be written for the combined main components, from which the main component mole fraction ξ_θ and η_θ are obtained as functions of S_θ, and Equations (95) for a and (96) for j are derived. Third, material balance equations will be written for light component, from which its mole fractions x_θ and y_θ are obtained, and Equation (94) for ψ is derived.

(1) All Components. The over-all material balance equation is:

$$J - T = H - S \qquad (109)$$

The equation for a material balance between the tails end of the stage and a point θ fraction from the feed end is:

$$J_\theta = S_\theta + J - T \qquad (110)$$

Since the molal velocity of all components through the screen is N, the differential material balance equation for all compo-

† On a separating agent-free basis.

nents in the heavy stream is:

$$N = \frac{dS_\theta}{A\,d\theta} \qquad (111)$$

By integrating this equation, the following is obtained:

$$S_\theta = S + NA\theta$$

and

$$T = S + NA$$

so that

$$J_\theta = J - NA(1-\theta)$$

and

$$H = J - NA \qquad (112)$$

(2) Main Components. The over-all material balance equation for the main components is:

$$S\xi = H\eta + T\xi_T \qquad (113)$$

The equation for a material balance between the tails end of the stage and θ is:

$$J_\theta \eta_\theta = S_\theta \xi_\theta - T\xi_T \qquad (114)$$

An expression for η_θ is obtained by eliminating J_θ from (110) and (114):

$$\eta_\theta = \frac{S_\theta \xi_\theta - T\xi_T}{S_\theta + J - T} \qquad (115)$$

At the point θ, the differential material

balance equation for the combined main components in the heavy stream is:

$$\frac{d(S_\theta \xi_\theta)}{A\,d\theta} = N_1 + N_2 = N - N_0 \qquad (116)$$

A differential equation for the variation of ξ_θ with S_θ is obtained by dividing (116) by (111):

$$\frac{d(S_\theta \xi_\theta)}{dS_\theta} = \frac{N - N_0}{N} \qquad (117)$$

The molal velocity of main components through the screen, $N - N_0$, is obtained from (28), which, in the notation of the present section, is:

$$N - N_0 = N \frac{\eta_\theta - \xi_\theta e^{-U}}{1 - e^{-U}} \qquad (118)$$

By combining (117) and (118) and simplifying, the following is obtained:

$$\frac{d\xi_\theta}{dS_\theta} = \frac{\eta_\theta - \xi_\theta}{S_\theta (1 - e^{-U})} \qquad (119)$$

η_θ may be replaced by its value from (115):

$$\frac{d\xi_\theta}{dS_\theta} = \frac{(T-J)\xi_\theta - T\xi_T}{S_\theta (S_\theta + J - T)(1 - e^{-U})} \qquad (120)$$

Variables in (120) are readily separated, and the equation may be integrated, subject

Stage Properties	Value	Source
Recovery, h	0.5	$V = L$
Ratio of separating agent to stage feed, p	1.9	Specified
Dimensionless ratio of screen area to stage feed, q	1.0	Specified
Mole fraction main components in stage feed, ξ	0.9	Specified
Mole fraction main components in heads, η	0.257	(102) & (103)
Reduced molal velocity through screen, U	0.15	(102) & (103)
Enrichment factor, ψ	0.0202	(101)
Separating agent: upflow ratio, j	4.22	(98)
Screen area: upflow ratio, a, sq.ft./(lb.mole) (sec.)	3.52×10^3	(97)
Characteristics of Largest Stage (x=0.9894)		
Upflow, V, lb.moles/sec.	1.83×10^{-2}	(83)
Separating agent rate, J, lb.moles/sec.	7.73×10^{-2}	jV
Screen area, A, sq.ft.	645	aV
Number of Stages		
Stripping	666	
Rectifying	11	
Total	677	(87)
Total Separating Agent Flow, lb./sec.	15.10	(93) or (105)
Total Screen Area, sq.ft.	70,000	(92) or (104)

to the boundary conditions that $\xi_o = \xi_r$ at $S_o = T$:

$$\frac{\xi_o}{\xi_r} =$$

$$\frac{J}{J-T}\left[\frac{T(S_0+J-T)}{JS_0}\right]^{\frac{1}{1-e^{-U}}} - \frac{T}{J-T}$$ (121)

At the feed end of the stage, $S_0 = S$ and $\xi_o = \xi$, so that:

$$\frac{\xi}{\xi_r} = \frac{J}{J-T}\left(\frac{TH}{JS}\right)^{\frac{1}{1-e^{-U}}} - \frac{T}{J-T}$$ (122)

ξ_r in this equation is to be replaced by the recovery of main components in the heads fraction, h, by using the relation:

$$h = 1 - \frac{T\xi_r}{S\xi}$$ (123)

and by making use of (109) to replace $J - T$ by $H - S$:

$$h = \frac{\left(\frac{TH}{SJ}\right)^{\frac{1}{e^U-1}} - 1}{\left(\frac{TH}{SJ}\right)^{\frac{1}{e^U-1}} - \frac{S}{H}}$$ (124)

Next, $p = J/S$ is obtained as a function of h, η/ξ and U by substituting for T the value $J + S - H$ and for H the value $hS\xi/\eta$, and solving for J/S:

$$p = J/S = \frac{\frac{h\xi}{\eta} - 1}{1 - \frac{\eta}{h\xi}\left(\frac{1-\eta/\xi}{1-h}\right)^{e^U-1}}$$ (125)

Equation (96) for j is obtained by the relation $j = p/\xi h$.

To derive Equation (95) for a from (125), we note that

$$a = A/H\eta = \frac{1}{N\eta}\left(\frac{J}{H} - 1\right)$$ (126)

since $A = (J-H)/N$, from (112). By substituting for J its value from (125), for H the expression $hS\xi/\eta$, and for N the expression $UD_o\rho/Z$, Equation (95) results.

3. Light Component. Derivation of Equation (94) for ψ requires evaluation of the light component mole fraction, x_0.

The over-all material balance equation for light component is:

$$S\xi x = H\eta y + T\xi_r x$$ (127)

The equation for a material balance between the tails end of the stage and θ is:

$$J_\theta \eta_\theta y_\theta = S_o \xi_o x_o - T\xi_r x$$ (128)

An expression for $y_\theta - x_\theta$ is obtained by eliminating $J_\theta \eta_\theta$ by means of (114)

$$y_\theta - x_\theta = \frac{T\xi_r(x_\theta - x)}{S_o\xi_o - T\xi_r}$$ (129)

At the point θ, the differential material balance equation for light component in the heavy stream is:

$$\frac{d(S_o\xi_o x_o)}{A\,d\theta} = N_1$$ (130)

By dividing (130) by (111), there results:

$$\frac{d(S_o\xi_o x_o)}{dS_o} = N_1/N$$ (131)

But

$$\frac{d(S_o\xi_o x_o)}{dS_o} = \frac{x_\theta d(S_o\xi_o)}{dS_o} + S_o\xi_o\frac{dx_o}{dS_o}$$ (132)

and $d(S_o\xi_o)/dS_o$ is given by (117), so that we have

$$S_o\xi_o\frac{dx_o}{dS_o} = \frac{N_1 - (N-N_0)x_o}{N}$$ (133)

The molal velocities N_0 and N_1 are expressible in terms of the mole fractions on both faces of the screen by means of Equations (118) and (37) respectively. The subscript θ is appended to η, ξ, y and x in the latter equation. When these substitutions are made, and (133) is divided by (119),

$$\frac{dx_o}{d\xi_o} = \frac{(y_o - x_o)\eta_o}{\xi_o(\eta_o - \xi_o)} + \frac{x_o(1-x_o)}{\xi_o}\left(\frac{\gamma U e^{-U}}{1 - e^{-U}}\right)$$ (134)

is obtained. η_o and y_o in this equation may be replaced by functions of ξ_o and x_o by means of (115) and (129):

$$\frac{dx_o}{d\xi_o} + \frac{(x_o - x)}{\xi_o\left(1 + \frac{J-T}{T\xi_o}\xi_o\right)} = \frac{\gamma x(1-x)U e^{-U}}{\xi_o(1-e^{-U})}$$ (135)

where the constant value of $x(1-x)$ has been substituted for $x_o(1-x_o)$ in the last term.

This is a first-order, linear differential equation in $(x_o - x)$ vs. ξ_o. The solution of this equation, subject to the boundary condition $x_o = x$ at $\xi_o = \xi_r$ is:

$$x_o - x = \frac{\gamma x(1-x)U e^{-U}}{1 - e^{-U}}\frac{T\xi_r + (J-T)\xi_o}{\xi_o(J-T)}\ln\left[\frac{T\xi_r + (J-T)\xi_o}{J\xi_r}\right]$$ (136)

The stage enrichment factor, ψ, is given by:

$$\psi = \frac{y - x}{x(1-x)} = \frac{z - x}{hx(1-x)}$$ (137)

But $z - x$ may be obtained from (136) by setting $\xi_o = \xi$, so that

$$\psi = \frac{\gamma U e^{-U}}{1 - e^{-U}}\frac{T\xi_r + (J-T)\xi}{h\xi(J-T)}\ln\left[\frac{T\xi_r + (J-T)\xi}{J\xi_r}\right]$$ (138)

The second factor of this equation may be replaced by

$$\frac{1 - \frac{\eta}{\xi}}{h - \frac{\eta}{\xi}}$$

because of the over-all material balance Equations (109) and (113) and the definition of h. The argument of the logarithm may be replaced by

$$\left(\frac{TH}{JS}\right)^{\frac{1}{1-e^{-U}}}$$

because of Equation (122) for ξ/ξ_r. With these changes, Equation (138) becomes:

$$\psi = \frac{\gamma U e^{-U}}{(1-e^{-U})^2}\frac{1 - \eta/\xi}{h - \eta/\xi}\ln\left(\frac{TH}{JS}\right)$$ (139)

From (124) it may be seen that

$$\frac{TH}{JS} = \left(\frac{1 - \frac{hS}{H}}{1 - h}\right)^{e^U-1}$$ (140)

Equation (94) for ψ results when hS/H is replaced by η/ξ in (140) and (140) is substituted into (139).

8. Local Performance of Screen for Hydrogen Separation

In addition to isotope separation, mass diffusion may find commercial application in the extraction of hydrogen or helium from mixtures with heavier gases, particularly when the gases are at low pressure and waste heat at low temperature is available. These conditions are met often in coke plants, so that mass diffusion may find commercial application in separating hydrogen from coke-oven gas, using low-pressure steam as separating agent. Design principles for this application are outlined in the remainder of this paper.

It will be assumed that the non-hydrogen constituents of coke-oven gas

have diffusional characteristics similar to air. The diffusion coefficients for this system are obtained from International Critical Tables, vol. 5, p. 62 (Table D). The diffusion coefficient of hydrogen

into air has little effect on the design; to simplify the treatment, it will be assumed that

$$\rho D_{12} = \rho D_{01} = 2.835 \times 10^{-6}$$

In deriving equations for the local screen performance in this case, we will denote mole fractions within the screen by v, in the light stream by y, and in the heavy stream by x. Molal velocities,

TABLE D

Hydrogen into steam	$\rho D_{01} = 2.835 \times 10^{-6}$ lb.mole/(ft.)(sec.)
Air into steam	$\rho D_{02} = 0.831 \times 10^{-6}$ lb.mole/(ft.)(sec.)
Hydrogen into air	$\rho D_{12} = 2.30 \times 10^{-6}$ lb.mole/(ft.)(sec.)

as usual, will be denoted by N. Subscript $(_0)$ will refer to separating agent, $(_1)$ to hydrogen, and $(_2)$ to the heavier components from, which hydrogen is to be separated. With this notation, and with the relations $N_0 = N - N_1 - N_2$ and $v_0 = 1 - v_1 - v_2$, and with the assumption that $D_{12} = D_{01}$, the system of differential diffusion Equations (8) becomes:

Hydrogen:

$$\frac{dv_1}{dt} = \frac{Nv_1 - N_1}{\rho D_{01}} \quad (141.1)$$

Heavy Components:

$$\frac{dv_2}{dt} = \frac{N_1 v_2 - N_2 v_1}{\rho D_{01}}$$

$$+ \frac{(N - N_1)v_2 - N_2 + N_2 v_1}{\rho D_{02}}$$

$$(141.2)$$

The solution of (141.1) for hydrogen, subject to the boundary condition $v_1 = y_1$ at $t = 0$, is:

$$v_1 = (y_1 - N_1/N)e^{Nt/\rho D_{01}} + N_1/N$$

$$(142)$$

With the condition $v_1 = x_1$ at $t = Z$, the molal velocity of hydrogen is given by:

$$N_1 = N \frac{y_1 - x_1 e^{-U}}{1 - e^{-U}} \quad (143)$$

where

$$U = NZ/\rho D_{01} \quad (144)$$

To solve Equation (141.2), for heavy components, v_1 is eliminated by means of (142), and a new dimensionless parameter,

$$\Delta = \left(1 - \frac{N_1}{N}\right)\left(\frac{D_{01}}{D_{02}} - 1\right)U$$

$$(145)$$

is introduced:

$$\frac{dv_2}{dt} = \frac{U + \Delta}{Z} v_2$$

$$+ \frac{(y_1 - N_1/N)e^{Ut/Z}\Delta N_2}{Z(N - N_1)} - \frac{(U + \Delta)N_2}{ZN}$$

$$(146)$$

This is a first-order, linear differential equation in v_2, whose integrating factor is $e^{-(U+\Delta)t/Z}$. Its solution, subject to the boundary conditions $v_2 = x_2$ at $t = Z$ and $v_2 = y_2$ at $t = 0$, is:

$$y_2 - x_2 e^{-U-\Delta} =$$

$$- \frac{(y_1 - N_1/N)(1 - e^{-\Delta})N_2}{N - N_1}$$

$$+ \frac{(1 - e^{-U-\Delta})N_2}{N} \quad (147)$$

When this equation is solved for N_2, and N_1 is replaced by its value from (143), there results:

$$N_2 = N \frac{(1 - y_1) - (1 - x_1)e^{-U}}{1 - e^{-U}}$$

Equations (143) and (148) are the desired equations for molal velocities through the screen in the hydrogen separation case. The molal velocity of separating agent is obtained from

$$N_0 = N - N_1 - N_2. \quad (148a)$$

9. Extraction of Hydrogen by Mass Diffusion Column

The theory of a mass diffusion column for the extraction of hydrogen from heavier gases is more involved than for the isotope separation case because of the large difference in hydrogen mole fraction on opposite faces of the screen. As a consequence, explicit solution of the differential material balance equations is impossible, and recourse must be had to numerical methods. This section will describe a solution procedure and apply it to the separation of a gas containing 50% H_2 into a rich fraction containing 90% H_2 and a lean fraction containing 10%.

Schematic flow through this mass diffusion column and the nomenclature to be used in analyzing its performance are illustrated in Figure 6, and are the same as have been used in the isotope separation case.

In this notation, Equations (143), (148), and (148a) for N_1, N_2 and N_0, respectively, become:

Hydrogen:

$$\frac{N_1}{N} = \frac{\eta y - \xi x e^{-U}}{1 - e^{-U}} \quad (149.1)$$

Heavy Components:

$$\frac{N_2}{N} = \frac{(1 - \eta y) - (1 - \xi x)e^{-U}}{1 - e^{-U}} \cdot \frac{\eta(1 - y) - \xi(1 - x)e^{-U-\Delta}}{(1 - \eta y) - (1 - \xi x)e^{-U-\Delta}} \quad (149.2)$$

Separating Agent:

$$\frac{N_0}{N} = \frac{(1 - \eta y) - (1 - \xi x)e^{-U}}{1 - e^{-U}} \cdot \frac{(1 - \eta) - (1 - \xi)e^{-U-\Delta}}{(1 - \eta y) - (1 - \xi x)e^{-U-\Delta}} \quad (149.0)$$

A material balance on hydrogen between the bottom end of the column and a point in the stripping section where the mole fraction of hydrogen * in the light stream is y and in the heavy stream is x gives an equation for the downflow rate,* L:

$$L = \frac{B(y - x_B)}{y - x} \quad (150)$$

A differential material balance on hydrogen plus heavy components in the heavy stream may be expressed as:

$$\frac{dL}{dA} = -(N_1 + N_2) \quad (151)$$

$$\frac{y_2 - x_2 e^{-U-\Delta}}{(1 - y_1) - (1 - x_1)e^{-U-\Delta}} \quad (148)$$

The differential material balance for hydrogen in the heavy stream may be combined with (151) as in deriving Equation (51):

$$\frac{dx}{dA} = \frac{(N_1 + N_2)x - N_1}{L} \quad (152)$$

The amount of separating agent charged to the light stream per unit screen area, dJ/dA, depends on its molal velocity through the screen, N_0, and on the rate of change of its flow rate past the screen in the light stream, $(L - B)(1 - \eta)/\eta$, as given by Equation (153):

$$\frac{dJ}{dA} = N_0 + \frac{d}{dA}[(L - B)(1 - \eta)/\eta]$$

$$(153)$$

These four equations, together with Equations (149) for N_1, N_2 and N_0 give seven relations among the ten variables L, ξ, η, y, x, N_1, N_2, N_0, J and A. Before a solution can be given for the value of these variables at any point in the column or for the total amount of screen area and separating agent consumption needed in a given separation, it is necessary to specify three additional conditions. These conditions, for example, might consist in giving (1) the dependence of the hydro-

gen mole fraction * in the light stream, y, on its mole fraction * in the heavy stream, x, and (2) and (3) the dependence of the separating agent mole fraction in each stream, $1 - \eta$ and $1 - \xi$, on x.

One might choose these conditions to result in minimum total screen area, minimum separating agent consumption, or minimum total cost of producing hydrogen by such a column. Use of material balance equations (150)-(153)

* Separating agent-free basis.

to evaluate the total screen area and total separating agent consumption with the aid of the assumed relations $y(x)$, $\eta(x)$ and $\xi(x)$ will be illustrated.

By differentiating (150), it is seen that dL/dx is given by:

$$\frac{1}{L}\frac{dL}{dx} = \frac{1}{y-x} - \frac{x-x_B}{(y-x)(y-x_B)}\frac{dy}{dx}$$

(154)

But dL/dx may also be obtained by dividing (151) by (152):

$$\frac{1}{L}\frac{dL}{dx} = \frac{N_1+N_2}{N_1-x(N_1+N_2)}$$

(155)

so that:

$$\frac{1}{y-x} - \frac{x-x_B}{(y-x)(y-x_B)}\frac{dy}{dx}$$
$$= \frac{N_1+N_2}{N_1-x(N_1+N_2)} \quad (156)$$

By replacing N_1 and N_2 in (156) by their values in terms of U, x, $y(x)$, $\xi(x)$, and $\eta(x)$, through (149), Equation (156) may be used to determine U as a function of x.

To evaluate the screen area, Equation (152) is combined with Equation (155) and with Equation (144) defining U:

$$\frac{dA}{dx} = -\frac{Z}{\rho D_{01}}\frac{dL/dx}{U(N_1/N+N_2/N)}$$

(157)

The total screen area is obtained by integrating (157) in both the stripping and rectifying sections:

$$A = -\frac{Z}{\rho D_{01}}\left[\int_{x_B}^{x_F}\frac{(dL/dx)_B}{U(N_1/N+N_2/N)}dx + \int_{x_F}^{x_D}\frac{(dL/dx)_D}{U(N_1/N+N_2/N)}dx\right]$$

(158)

In this equation, $(dL/dx)_B$ refers to the stripping section and is obtained from (154); $(dL/dx)_D$ refers to the rectifying section and is obtained by differentiating

$$L = \frac{D(y_D-y)}{y-x}$$

(159)

x_D is the mole fraction of hydrogen in the heavy stream corresponding to the specified mole fraction y_D in the tops light stream.

When the design objective is to minimize the screen area, we have a variational problem in which the functions $y(x)$, $\xi(x)$ and $\eta(x)$ are to be determined such that (158) is a minimum, subject to (156) to determine $U(x)$.

To evaluate the separating agent consumption, (153) is combined with (152) and (155) to give:

$$\left(\frac{dJ}{dx}\right)_B =$$
$$\left[\frac{1}{\eta} - \frac{1}{N_1/N+N_2/N}\right]\left(\frac{dL}{dx}\right)_B$$
$$+ (L-B)\frac{d(1/\eta)}{dx} \quad (160)$$

The subscript B signifies that this equation refers to the stripping section.

The analogous equation for the rectifying section is:

$$\left(\frac{dJ}{dx}\right)_D =$$
$$\left[\frac{1}{\eta} - \frac{1}{N_1/N+N_2/N}\right]\left(\frac{dL}{dx}\right)_D$$
$$+ (L+D)\frac{d(1/\eta)}{dx} \quad (161)$$

The total separating agent consumption is obtained by integrating (160) over the stripping section and (161) over the enriching section:

$$J =$$
$$\int_{x_B}^{x_F}\left(\frac{dJ}{dx}\right)_B dx + \int_{x_F}^{x_D}\left(\frac{dJ}{dx}\right)_D dx$$

(162)

When the design objective is to minimize separating agent consumption, there is a variational problem in which $y(x)$, $\xi(x)$ and $\eta(x)$ are to be determined such that (162) is a minimum, subject to (156) to determine $U(x)$.

The general problem of minimizing (158) or (162) has not been solved. Instead, the problem has been attacked by trying a number of assumptions regarding $\xi(x)$, $\eta(x)$ and $y(x)$ and seeing which results in the smallest values of A or J. It is clear that increasing ξ reduces both A and J, so that the highest practicable value obtainable without refrigeration when steam is used as separating agent at atmospheric pressure has been assumed, namely, $\xi = 0.9$. It has been assumed that η is independent of x, and values of $\eta = 0.20$, 0.25 and 0.30 have been tried. It has been assumed that $y(x)$ is of the form

$$y(x) = \frac{ax}{ax+1-x}$$

(163)

and values of 2.1, 2.3 and 2.5 for a have been tried. The lowest separating-agent consumption was found for the combination $\eta = 0.25$, $a = 2.3$. It should be noted that these are not necessarily the optimum $\eta(x)$ and $y(x)$, because some functional forms other than those used might lead to a lower separating agent consumption.

As a specific example of this design method, the total screen area and total separating-agent consumption will be worked out for a column separating coke-oven gas containing 50% H_2 into a tops fraction containing 90% H_2* and a bottoms fraction containing 10% H_2 by mass diffusion into steam at atmospheric pressure. It will be assumed that $\xi = 0.9$, $\eta = 0.25$ and that $y(x)$ is given by (163), with $a = 2.3$. The calculation will be based on 2 moles of feed/sec., so that

$$B = D = 1.0$$

and

$$x_B = 0.1; \quad y_D = 0.9$$

Steps in the calculation are summarized in Table 5, which gives conditions at various mole fractions of hydrogen in the column.

The solution procedure is:

1. At a particular value of x in the stripping section, find the downflow rate, L, from

$$L = \frac{B[ax-(ax+1-x)x_B]}{(a-1)x(1-x)}$$

(164)

obtained from (150) and (163).

2. Evaluate dL/dx from

$$\frac{dL}{dx} =$$
$$L\left[\frac{a-(a-1)x_B}{ax-(ax+1-x)x_B} - \frac{1}{x} + \frac{1}{1-x}\right]$$

(165)

3. By trial, find a value of U which gives molal velocities N_1 and N_2 which satisfy (156).

4. Evaluate dA/dx from (157).

5. Evaluate dJ/dx from

$$\frac{dJ}{dx} = \left(\frac{1}{\eta} - \frac{N}{N_1+N_2}\right)\frac{dL}{dx}$$

(166)

obtained by setting $d\eta/dx = 0$ in (160). An analogous procedure is used for the rectifying section.

6. Evaluate the total screen area, A, and the total separating agent consumption, J, by graphical integration, e.g., by (162).

By integrating the tabulated values of dA/dx and dJ/dx, it is found that a

* Separating agent-free basis.
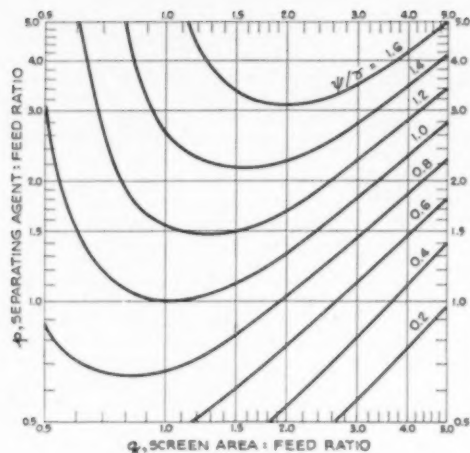
Fig. 10. Stage enrichment factor.
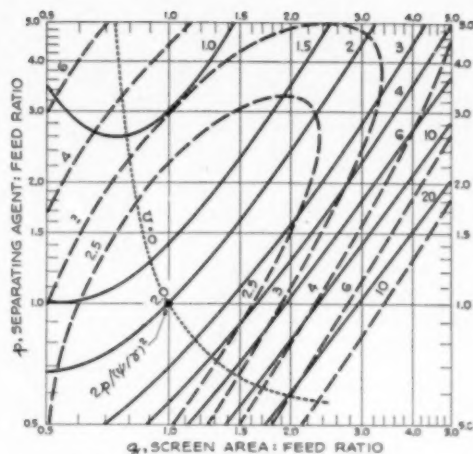
Fig. 11. Mass diffusion stage characteristics.
Total screen area is proportional to $2q/(\psi/\gamma)^2$ ———
Total separating agent consumption is proportional
to $2p/(\psi/\gamma)^2$ — — —

plant separating coke-oven gas containing 50% H_2 into tops containing 90% and bottoms containing 10% H_2 will require 26.00 $Z/\rho D_{01}$ sq.ft. of screen/mole of tops/sec. and will consume 19.84 moles of steam/mole of tops. A plant producing 1,000,000 cu.ft. of hydrogen/day will require 34,500 sq.ft. of screen ($Z = 0.111$) and 43,500 lb./hr. of steam.

The power which could be generated by this amount of saturated steam at 212° F. when condensed at 80° F. in a thermodynamically perfect engine is 3480 hp. The power required to separate this 1,000,000 cu.ft. of hydrogen/day in a reversible process is 39.3 hp. The thermodynamic efficiency of this mass diffusion separation is, therefore, 39.3/3480, or only 1.1%. Since an efficiency of around 15% can be obtained when hydrogen is separated by partial condensation at low temperature, it is evident that mass diffusion is at a serious disadvantage with respect to power cost. Its main advantage is in the simple type of equipment used, compared with a low-temperature plant.

10. Extraction of Hydrogen by Mass Diffusion Stage

When only a partial separation of hydrogen from heavier gases is to be effected, the stage type of mass diffusion is preferable to the column type, because of its simpler construction. Maier's experimental study (6) provides a wealth of information for design of a stage for partial separation of hydrogen by mass diffusion.

Figure 12 illustrates the flow of material into and out of a mass diffusion stage for hydrogen separation and the

TABLE 5.—CONDITIONS IN COLUMN FOR SEPARATION OF HYDROGEN FROM COKE-OVEN GAS BY MASS DIFFUSION INTO STEAM

Pressure = 1 atm.
Temp. = 212° F.

Mole fraction gas in heavy stream (ξ) = 0.90
Mole fraction gas in light stream (η) = 0.25
Basis, 2 moles feed/sec.

	Stripping Section					Rectifying Section			
	Bottoms				Feed	Feed			Tops
Mole fraction H₂† Heavy stream, x	0.10	0.20	0.30	0.40	0.50	0.50	0.60	0.70	0.796
Light stream, y	0.204	0.365	0.496	0.605	0.697	0.697	0.775	0.483	0.900
Gas downflow, L†, mole/sec.	1.00	1.606	2.02	2.46	3.03	1.03	0.714	0.399	0.000
Gas upflow, V†, mole/sec.	0.00	0.606	1.02	1.46	2.03	2.03	1.714	1.399	1.000
dL/dz	9.67	4.41	4.10	4.95	6.68	—3.47	—3.05	—3.38	—5.35
Molal Velocities $U = NZ/\rho D_{01}$	0.105	0.304	0.347	0.360	0.368	1.015	1.15	1.34	1.64
Hydrogen, N_1/N	—0.3013	—0.1588	—0.2280	—0.3318	—0.4457	0.0187	0.0333	0.0610	0.1069
Other comp., N_2/N	—1.1797	—0.1226	—0.0382	—0.0382	—0.0216	0.0732	0.0588	0.0437	0.0277
Steam, N_0/N	2.4810	1.2814	1.2877	1.3700	1.4673	0.9081	0.9079	0.8953	0.8654
$\dfrac{\rho D_{01}}{Z}\dfrac{dA}{dz}$	62.2	51.6	41.1	37.2	28.9	37.2	28.8	24.1	24.2
$\dfrac{dJ}{dz}$	45.2	33.3	30.7	33.2	41.0	23.9	20.6	18.8	17.6

† Separating agent-free basis.

principal variables which will be used in describing its performance. The three dimensionless ratios, p, q and U, which were introduced in analyzing stage performance for the isotope separation case, will also be useful for hydrogen separation.

10.1 Hydrogen Recovery. Equation (143) for the molal velocity of hydrogen through the screen (N_1), is similar to (118) for the molal velocity of main components in the isotope separation case. An equation for the fraction of hydrogen fed to the stage which is recovered in the heads fraction, h_1, may be written down by analogy with Equation (124) for the isotope separation case:

$$h_1 = \frac{\left(\dfrac{TH}{SJ}\right)^{\beta_1} - 1}{\left(\dfrac{TH}{SJ}\right)^{\beta_1} - \dfrac{S}{H}} \qquad (167)$$

where $\beta_1 = \dfrac{1}{e^U - 1}$

But $H/S = p - qU$, and $T/J = (1 + qU)/p$, so that

$$h_1 =$$

$$\frac{[(p - qU)(1 + qU)/p]^{\beta_1} - 1}{[(p - qU)(1 + qU)/p]^{\beta_1} - \dfrac{1}{p - qU}} \qquad (168)$$

10.2 Approximate Equations for Stage Characteristics. No simple, exact expression can be given for the recovery of heavy components, h_2, because of the complex character of Equation (148) for the molal velocity of heavy components. It is possible, however, to derive a simple, approximate expression for h_2 which is sufficiently exact for most practical applications. Such an approximate expression for h_2 is derived below, and other important stage characteristics are evaluated from it. These approximate stage characteristics are shown to be in tolerable agreement with Maier's experimental data in Section 10.3. Finally, in Section 10.4 exact stage characteristics are evaluated numerically for a particular set of conditions and shown to be close to the approximate equations about to be derived.

When the mole fraction of hydrogen is low, (y_1 and x_1 each $<< 1$), Equation (143) shows that $N_1/N << 1$. Under these circumstances $U + \Delta \cong UD_{01}/D_{02}$, and Equation (148) reduces to

$$N_2 = N \frac{y_2 - x_2 e^{-UD_{01}/D_{02}}}{1 - e^{-UD_{01}/D_{02}}} \qquad (169)$$

TABLE E

Moles	Feed	Heads	Tails
Hydrogen	0.50	0.25	0.25
Heavy components	0.50	0.0278	0.4722
All components	1.00	0.2778	0.7222
% H₂	50	90	34.6

It is shown in Section 10.4 that this expression is a valid approximation when y_1 and x_1 are not $<< 1$.

Since Equation (169) for the molal velocity of heavy components is similar to Equation (143) for hydrogen, an equation for the recovery of heavy components, h_2, may be written down by analogy with (168):

$$h_2 =$$

$$\frac{[(p - qU)(1 + qU)/p]^{\beta_2} - 1}{[(p - qU)(1 + qU)/p]^{\beta_2} - \dfrac{1}{p - qU}} \qquad (170)$$

where $\beta_2 = \dfrac{1}{e^{UD_{01}/D_{02}} - 1}$

An approximate equation for the stage separation factor, α, may be obtained as follows: From definitions of h_1 and h_2:

$$\frac{y_1}{y_2} = \frac{z_1 h_1}{z_2 h_2}$$

and

$$\frac{x_1}{x_2} = \frac{z_1(1 - h_1)}{z_2(1 - h_2)}$$

Therefore,

$$\alpha = \frac{y_1 x_2}{y_2 x_1} = \frac{h_1(1 - h_2)}{h_2(1 - h_1)} \qquad (171)$$

Since h_1 is given by (168) and h_2 approximately by (170), an approximate equation for α is:

$$\alpha = \frac{[(p - qU)(1 + qU)/p]^{\beta_1} - 1}{[(p - qU)(1 + qU)/p]^{\beta_2} - 1} \qquad (172)$$

In designing a mass diffusion stage for extraction of hydrogen, the most important quantities are the screen area and steam consumption rate per unit feed rate required to obtain the specified separation factor and hydrogen recovery. Since the reduced velocity, U, is of less interest than q and p, which are proportional to the screen area and steam consumption, respectively, it is convenient to eliminate U from Equations (168) and (172). This elimination has been carried out numerically, using $D_{01}/D_{02} = 3.408$, with the results shown in Figure 13. The upper chart refers to a constant value for the ratio q/p of 0.5; the lower, for a constant value of 1.0. In each chart, the separation factor, α, has been plotted against the hydrogen recovery, h_1, for the constant values of the steam-feed ratio p indicated on the individual lines.

As an example of the use of these charts, the extraction of a heads fraction containing 90% H₂, with a recovery of 50% from a feed containing 50% H₂, will be considered. The material balance for this separation is given in Table E.

The separation factor, then, is

$$\alpha = \frac{(0.90)}{(0.10)} \frac{(0.654)}{(0.346)} = 17.0$$

From Figure 13 it is seen that the following values of q and p will give a
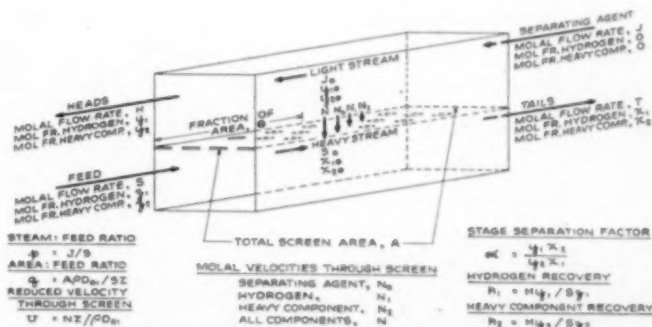
Fig. 12. Nomenclature for mass diffusion stage for hydrogen separation.
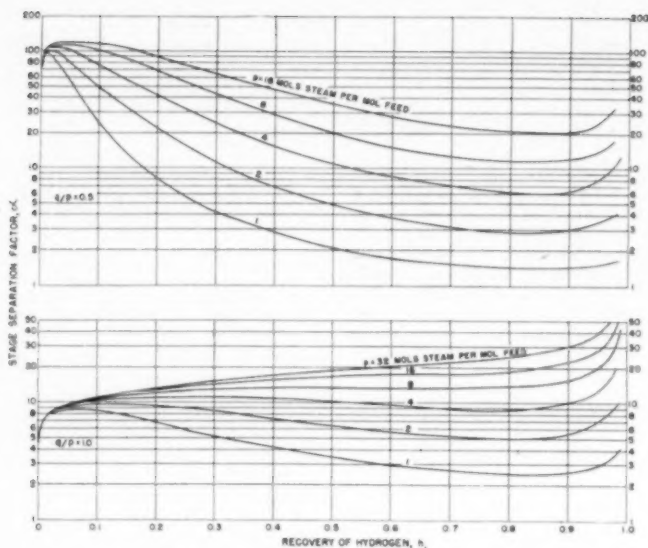
Fig. 13. Characteristics of mass diffusion stage for hydrogen production.
p = moles steam/mole feed J/S
q = reduced screen area/mole feed, $(A/S)(\rho D_{01}/Z)$.

separation factor of 17.0 at 50% H_2 recovery:

q/p	0.5	1.0
p	7	16
q	3.5	16

Clearly, the pair of values in the first column is preferable.

From these values of p and q, the steam consumption rate and screen area required to produce 1,000,000 std. cu.ft./day of hydrogen from feed containing 10% moisture will be evaluated. The feed rate S to produce this amount of hydrogen with 50% recovery is

$$S = \frac{1,000,000}{380 \times 0.5 \times 0.5 \times 0.9 \times 86,400}$$

$$= 0.1354 \text{ lb. mole/sec.}$$

The steam consumption rate, given by $J = pS$, is therefore 0.948 lb. mole/sec., or 61,400 lb./hr. The screen area, given by $A = qSZ/\rho D_{01}$, is

$$A = \frac{3.5 \times 0.1354 \times 0.111}{2.835 \times 10^{-6}}$$

$$= 18,600 \text{ sq.ft.}$$

for $Z = 0.111$ ft.

10.3 Comparison with Maier's Experimental Results. Of the types of apparatus tested by Maier (6), his unit L, using a No. 98 Alundum extraction thimble, most closely resembles the countercurrent mass diffusion stage which has been treated in this section. This thimble was 2 mm. thick and had an area of 188.4 sq.cm. and a

nominal porosity of 47.4%. Its O.D. was 2.0 cm. The outer, annular passage carrying the light stream had a cross-sectional area of 9.4 sq.cm., from which an O.D. of 4.0 cm. and a clearance of 1.0 cm. may be inferred. The inner, annular passage carrying the heavy stream is stated to have had a cross-sectional area of 2.9 sq.cm., which is incompatible with its O.D. of 1.6 cm. The clearance of this passage was probably around 0.5 cm. With the throughputs reported, the flow was always laminar. The effective diffusion length of this apparatus, calculated as described in Section 5 without making allowance for its annular character and with the assumption that the fractional free area of the screen was the same as its porosity, is:

Outer passage	$1.0 \times 13/35$ =	0.37
Inner passage	$0.5 \times 13/35$ =	0.19
Screen	$0.2/0.477$ =	0.42
		0.98 cm.
		(0.0321 ft.)

Since the gas flow channels of the diffusion screen were the irregular voids of a packed bed rather than uniform cylindrical holes, the fractional free area of the screen must have been less than its porosity, and the above estimate of the diffusion length of the screen must be less than its actual diffusion length. It will be noted that the experimental data may be used to obtain an approximate value of 0.10 ft. for the actual diffusion length of this apparatus.

This apparatus was tested by Maier on mixtures of hydrogen and nitrogen containing 6.0, 11.1, 26.5, 41.0, 55.5, 77.0 and 90.0% hydrogen, at gas feed rates of 0.2, 0.6, 1.0 and 1.4 l./min., and with the fraction of gas diffused ranging from 0 to 100%. Steam consumption rates varying from less than 2 to around 6 g./min. were used.

Complete analysis of the data is not possible because only approximate values are given for the steam consumption, the conditions at which the volume of the feed was measured are not stated, and the fraction of steam passing through the screen is not reported. In correlating the data, it has been assumed that the normal steam rate, reported as between 2 and 4 g./min., was actually 3.0, and that feed volumes were measured for dry gas at 25° C.

Maier's results are expressed as plots of the "extraction," E, the "clean-up factor," P, and the "countercurrent concentration ratio," Λ, versus "throttling factor," x, at constant feed composition, feed rate and steam rate. These four variables are expressed below in terms of the variables of Figure 12:

Maier   This Paper

$E = h_1$ (hydrogen recovery)

$P = x_1 z_2/x_2 z_1$

$\Lambda = y_1(z_1 + z_2)/(y_1 + y_2)z_1$

$x = h_1 + h_5$ (recovery of hydrogen plus heavy components)

The stage separation factor may be expressed as a function of P and Λ by:

$$a = \frac{y_1 x_2}{x_1 y_2} = \frac{\Lambda(1-z)}{(1-\Lambda z)P}$$

where $z = z_1/(z_1 + z_5)$, the mole fraction of hydrogen in feed on a steam-free basis.

Maier's experimental results for a feed rate of 0.6 l./min. and a steam rate of 3.0 g./min. have been converted to stage separation factors and plotted against hydrogen recovery in Figure 14. Each set of points represents one of the compositions studied by Maier. The reported feed and steam rates correspond to $p = 6.8$ and $q = 0.639/Z$. The full line of the figure shows the dependence of stage separation factor on hydrogen recovery predicted by the simple theory which led to Equations (168) and (172) for the reported value of $p = 6.8$, and a value of $q = 6.5$, c rresponding to $Z = 0.0984$ ft. This theoretical line is in good agreement with Maier's results for feed compositions of 6.0 and 77.7% hydrogen, but is somewhat higher than the points at intermediate feed compositions. The scatter of the individual points, however, is no greater than would be expected for variations in the steam rate from 2.0 to 4.0 g./min., with the exception of the two low points at 11.1% hydrogen, which are obviously in error.

The dashed line is the theoretical curve for $p = 6.8$ and $q = 8.0$, corresponding to $Z = 0.080$ ft. Although it fits the entire group of points somewhat better than $q = 6.5$, it is a less satisfactory fit of the trend of a vs. h_1 observed at any one feed composition. For this reason, a value of $q = 6.5$, corresponding to $Z = 0.1$ ft., is regarded as representative of the data.

The fact that the line for $q = 6.5$ falls somewhat above the average of the observed points is attributed to separative inefficiencies not taken into account by theory. These might include variations in pressure difference across the screen from point to point, and non-uniformity of hole size, permitting a greater molal velocity of steam through some holes than others.

10.4   Exact Theory of Stage Characteristics. To show that the differences noted between the experimental results and the simple, approximate theory is not due to errors introduced by the approximations, a curve of α versus h for $p = 6.8$, $q = 6.5$, and $z = 0.555$ was worked out without using the approximation for the molal velocity of heavy components introduced by Equation (169). This curve, represented by the dashed line of Figure 15, is compared with the predictions of the simple theory, represented by the full line. The difference between the simple and exact theories is much less than the difference between the former and the experimental points.

The nomenclature of Figure 12 is used in deriving an exact expression for the stage separation factor, α. Since Equation (143) for the molal velocity of hydrogen is of the same form as (118) for the main components in the isotope separation case, the mole fraction of hydrogen in the heavy stream at a fraction θ of the area from the feed end to the tails end of the stage may be written by analogy with Equation (121), by substituting the mole fraction of hydrogen ($x_{1\theta}$) for the mole fraction of main components (ξ_θ). With this substitution, result of dividing Equation (121) by Equation (122) is:

$$\frac{x_{1\theta}}{z_1} = \frac{J\left(\frac{TJ_\theta}{JS_\theta}\right)^{\frac{1}{1-e^U}} - T}{J\left(\frac{TH}{JS}\right)^{\frac{1}{1-e^U}} - T}$$

(173)

where J_θ has been written for $S_\theta + J - T$. By material balance, the mole fraction of hydrogen in the light stream at the same point is:

$$y_{1\theta} =$$

$$\frac{S_\theta x_{1\theta} - T x_1}{J_\theta} = z_1 \frac{\left(\frac{TJ_\theta}{JS_\theta}\right)^{\frac{1}{e^U - 1}} - 1}{\frac{H}{S}\left(\frac{TH}{JS}\right)^{\frac{1}{e^U-1}} - 1}$$

(174)

Since

$$S_\theta = S(1 + qU\theta)$$
$$J_\theta = S[p - qU(1 - \theta)]$$
$$T = S(1 + qU)$$
$$H = S(p - qU)$$

and

$$J = Sp$$

these equations give $x_{1\theta}$ and $y_{1\theta}$ as functions of θ, for assigned values of p, q and U.

N_1/N may be obtained as a function of θ by substituting these values of $x_{1\theta}$ and $y_{1\theta}$ in (143). From (148), we see that N_2/N is of the form:

$$N_2/N = \Gamma(y_{2\theta} - x_{2\theta}e^{-U-\Delta})$$

(175)

where

$$\Gamma = \frac{(1 - y_{1\theta}) - (1 - x_{1\theta})e^{-U}}{(1 - e^{-U})[(1 - y_{1\theta}) - (1 - x_{1\theta})e^{-U-\Delta}]}$$

(176)

and

$$\Delta = \left(1 - \frac{N_1}{N}\right)\left(\frac{D_{o1}}{D_{o2}} - 1\right)U$$

(177)

Since $y_{1\theta}$, $x_{1\theta}$, and N_1/N are known functions of θ, Γ and Δ are known functions of θ, also.

A differential equation for the mole fraction of heavy component in the heavy stream, $x_{2\theta}$, is obtained from the differential material balance for heavy component:

$$\frac{d(S_\theta x_{2\theta})}{NA\,d\theta} = \frac{N_2}{N} = \Gamma(y_{2\theta} - x_{2\theta}e^{-U-\Delta})$$

(178)

The mole fraction of heavy component in the light stream, $y_{2\theta}$, may be expressed in terms of $x_{2\theta}$ by means of a material balance on this component between area θ and the tails end of the stage:

$$y_{2\theta} = \frac{S_\theta x_{2\theta} - T x_2}{J_\theta}$$

(179)

By eliminating $y_{2\theta}$ and substituting qUS for NA in Equation (178)

$$\frac{1}{qU}\frac{dx_{2\theta}}{d\theta} + $$

$$\left[\frac{S(1 + \Gamma e^{-U-\Delta})}{S_\theta} - \frac{S\Gamma}{J_\theta}\right]x_{2\theta}$$

$$= -\frac{\Gamma ST x_2}{J_\theta S_\theta}$$

(180)

is obtained. This is a first-order, linear
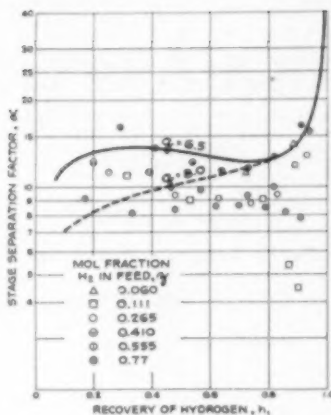
Fig. 14. Comparison of simple theory (line) with Maier's measurements (points) $p = 6.8$.

differential equation in $x_{2\theta}$, whose integrating factor is e^{I_θ}, where

$$I_\theta = qU\int_0^\theta \left[\frac{S(1 + \Gamma e^{-U-\Delta})}{S_\theta} - \frac{S\Gamma}{J_\theta}\right]d\theta$$

(181)

Its solution, subject to the conditions

$$x_{2\theta} = z_2 \text{ at } \theta = 0$$
$$x_{2\theta} = x_2 \text{ at } \theta = 1$$

is:

$$\frac{x_2}{z_2} = \frac{1}{e^{I_T} + qUST\int_0^1 \frac{\Gamma e^{I\theta}d\theta}{J_\theta S_\theta}}$$

(182)

Thus, for assigned values of p, q, U, z_1 and z_2, x_2/z_2 may be evaluated by carrying out two numerical integrations. Since

$$1 - h_2 = \frac{T x_2}{S z_2}$$

(183)

an exact expression for the separation factor, α, is obtained from (171), using (168) for h_1 and (183) for h_2. This procedure was used to calculate the dotted curve of Figure 15, with $p = 6.8$, $q = 6.5$, $z_1 = 0.555$, $z_2 = 0.445$.

Notation (Part II)

a = ratio of stage screen area to upflow,[*]   (sq.ft.) (sec.)/lb.mole, A/V

A = stage screen area, sq.ft.
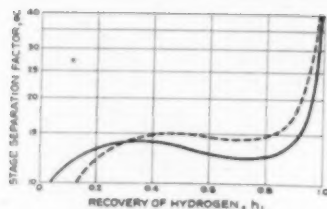
Fig. 15. Comparison of simple and exact theory.

$p = 6.8$, $q = 6.5$, $z_1 = 0.555$, $z_2 = 0.445$.

Simple ——— ; Exact - - - -

B = bottoms flow rate,* lb.mole /sec.

D_{ij} = diffusion coefficient of indicated pair of components, sq.ft./sec.

D_o = mean diffusion coefficient, sq.ft./sec., Eq. (15)

e = base of natural logarithms

F = feed rate,* lb.mole/sec.

h = recovery of main components, $V/(L+V)$ or $H\eta/S\xi$

h_1 = recovery of hydrogen, Hy_1/Sx_1

h_2 = recovery of heavy components, Hy_2/Sx_2

H = stage heads flow rate, lb. mole/sec., Figs. 9 and 12

I = integrating factor, Eq. (181)

j = ratio of separating agent to upflow,* J/V

J = flow rate of separating agent, lb.mole/sec.

L = downflow rate of heavy stream,* lb. mole/sec., Figs. 6 and 8

n = number of stages

N = total number of stages

N = molal velocity, lb.mole/ (sq.ft.) (sec.)

p = ratio of separating agent to stage feed rate, J/S or $jh\xi$

q = dimensionless ratio of screen area to stage feed rate, sq.ft.sec./lb.mole, $D_o\rho A/SZ$ or $aD_o\rho\xi h/Z$

S = stage feed rate, lb.mole/ sec., Figs. 9 and 12

T = stage tails flow rate, lb. mole/sec., Figs. 9 and 12

U = reduced molal velocity through screen, $NZ/D_{01}\rho$ or $NZ/D_o\rho$

v = mole fraction light component* within hole of screen, Fig. 5

V = upflow rate of light stream,* Figs. 6 and 8

x = mole fraction of light component in heavy stream on separating agent-free basis, Figs. 5 and 6

x = in stage process, mole fraction of light component in stage tails on separating agent-free basis, Fig. 9

x_0, x_1, x_2 = in stage process, the mole fraction of the designated component in stage tails, Fig. 12

x_θ = mole fraction of light component in heavy stream at point θ on separating agent-free basis, Fig. 9

$x_{0\theta}, x_{1\theta}, x_{2\theta}$ = mole fraction of the designated component in heavy stream at point θ, Fig. 12

$x_i(x_j)$ = mole fraction of ith (jth) component

y = mole fraction of light component in light stream on separating agent-free basis, Figs. 5 and 6

y = in stage process, mole fraction of light component in stage heads on separating agent-free basis, Fig. 9

y_0, y_1, y_2 = in stage process, mole fraction of the designated component in stage heads, Fig. 12

y_θ = mole fraction of light component in light stream at point θ on separating agent-free basis, Fig. 9

$y_{0\theta}, y_{1\theta}, y_{2\theta}$ = mole fraction of designated component in light stream at point θ, Fig. 12

z = mole fraction of light component in feed on separating agent-free basis, Fig. 9

Z = effective diffusion length of screen and light and heavy streams, ft., $Z_L + Z_2/\lambda + Z_H$

a = stage separation factor, $y_1 x_2/y_2 x_1$

$\beta_1 = 1/(e^U - 1)$

$\beta_2 = 1/(e^{UD_{01}/D_{02}} - 1$

γ = separability, Eq. (14)

Γ = Eq. (176)

Δ = function of diffusion coefficients, Eq. (145)

η = in stage process, mole fraction of main components in stage heads, Fig. 9

η_θ = mole fraction of main components at point θ in light stream, Fig. 9

θ = fraction of stage screen area from feed end of stage to point under consideration, Figs. 9 and 12

ξ_T = mole fraction of main components in stage tails

ξ = in stage process, mole fraction of main components in stage feed, Fig. 9

ξ_θ = mole fraction of main components at point θ in heavy stream, Fig. 9

$\pi(x_F, x_B)$ = separation potential for stripping section, Eq. (57)

$\pi(x_F, y_D)$ = separation potential for rectifying section, Eq. (59)

ρ = molal density, lb.mole/ cu.ft.

ψ = stage enrichment factor, $(y-x)/x(1-x)$

SUBSCRIPTS:

o = separating agent

1 = light component, or hydrogen

2 = heavy component

B = bottoms or stripping section

D = tops or rectifying section

F = feed

T = tails stream

θ = point within stage

* On separating agent-free basis.

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(THE END)

SWEEP DIFFUSION GAS SEPARATION PROCESS

PART II

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P ART I of this article which was published in the February issue, covered the theoretical analysis of a new gas separation process known as "sweep diffusion." In this installment the experimental work, including the comparison of theory with experiment, applications, and conclusions, are described.

Experimental
Apparatus and Experimental Procedures

The sweep diffusion process has been investigated experimentally, and the design and performance of three laboratory columns are discussed. The summary of the experimental data and results of these investigations is presented in Table 1.

Experimental Sweep Diffusion Columns.

Each column consists of an annular separating zone with a liquid curtain flowing down one of the boundary walls (Figs. 9, 11, 12). Sweep vapor is introduced into the annulus and diffuses across the working space to the liquid curtain where it is condensed, and the downflowing liquid is collected in a reservoir at the base of the column. The liquid is pumped from this reservoir into a distributor which introduces liquid around the top of the liquid guide tube. Countercurrent flow of the gases in the annulus is established as a result of the drag of the downflowing liquid curtain.

Feed gas is introduced into the working space at an intermediate point along the column. The top product is withdrawn from the top extremity of the separating zone, and the bottom product is withdrawn from the gas space in the liquid reservoir at the base of the column.

The three laboratory columns, though similar, are different in many respects. Columns $M1$ (Fig. 9) and $S3$ (Fig. 11) are made of glass whereas column $S5$ (Fig. 12) is made of metal. In columns $M1$ and $S5$, the sweep vapor is introduced into the working space throughout the length of the enriching and stripping sections of the column; however, in column $S3$, the vapor is introduced only at the bottom of each section. The vapor diffuses radially inward in

column $S3$ but diffuses radially outward in columns $M1$ and $S5$.

In columns $M1$ and $S5$ there is no provision for insuring dry vapor feed, and the measured vapor rate includes any condensate formed in the vapor inlet tube. In column $S3$, any condensate formed in the vapor inlet jackets is withdrawn from the base of each jacket, and therefore, the measured vapor rate for column $S3$ includes only the vapor condensed within the column.

The liquid curtain distributor in columns $S3$ and $S5$ consists of an annular orifice. A

perforated sparger ring is utilized as a liquid distributor in column $M1$. The width of the distributor orifices in columns $S3$ and $S5$ is 0.4 mm. and 0.38 mm., respectively.

In the runs made with column $S3$, utilizing ammonia as the sweep vapor, dilute acetic acid is used for the liquid curtain, and the effluent acid from the reservoir at the base of the column flows through a needle valve to the drain. The liquid curtain feed is pumped from an acid make-up reservoir into the liquid curtain distributor, and tap water flows into the make-up reservoir at a rate which is manually ad-
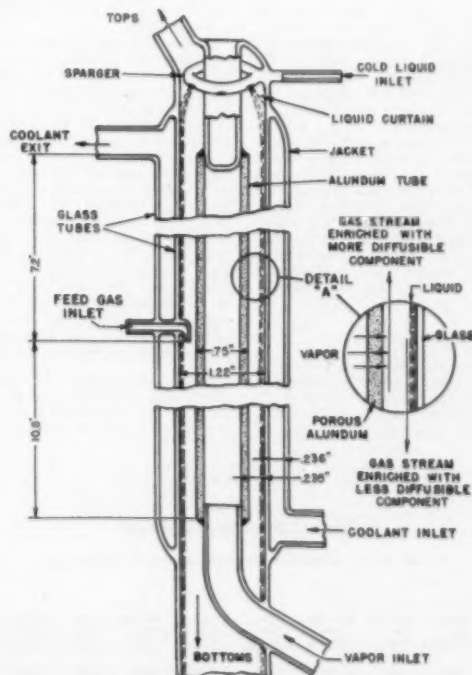
Fig. 9. Sectional view of sweep diffusion column M1.

Column M1; Hydrogen-Natural Gas Separations;
Steam Sweep Vapor; Water Liquid Curtain

Run No.	Mole % H₂ in Feed	Mole % H₂ in Bottoms	Mole % H₂ in Tops	Bottoms Flow S.C.F.H.	Tops Flow S.C.F.H.	Feed Rate S.C.F.H.	Tops to Feed Ratio	Bottoms Temp. °C.	Tops Temp. °C.	Column Pressure p.s.i.a.	Vapor Consumption lbs./hr.	Liquid Curtain Feed Pressure Drop, cm.Hg.	Vapor Temp. °K.
M1- 4	46.6	6.8	78.2	0.374	0.447	0.821	0.545	36.3	36.0	17.5	1.77	-	-
5	44.9	37.7	50.3	4.21	4.44	8.65	0.513	23	32	18.0	1.41	-	-
6	44.9	26.5	50.1	2.03	6.53	8.56	0.763	32.4	32.5	17.9	1.42	-	-
7	44.9	44.3	47.2	6.6	2.0	8.6	0.233	32.0	32.0	17.6	0.90	-	-
8	44.9	40.2	53.4	5.65	2.79	8.44	0.330	33.9	33.0	17.4	1.46	-	-
9	44.9	35.7	50.8	3.20	5.26	8.46	0.622	33.5	32.5	17.9	1.43	-	-
10	44.9	36.5	52.7	3.94	4.31	8.25	0.522	37.0	45.0	17.4	2.00	-	-
11	44.9	30.2	52.0	2.99	5.78	8.27	0.699	36.5	50.0	17.3	2.01	-	-
12	44.9	36.4	52.3	4.00	4.62	8.62	0.536	39.8	52.8	17.4	2.1	-	-
18	45.9	39.7	51.7	4.18	4.47	8.65	0.517	32.0	30.0	17.5	1.35	-	-
19	45.9	44.1	61.3	7.83	1.20	9.03	0.132	33.0	31.0	17.5	1.45	-	-
20	45.9	17.5	46.7	0.95	8.40	9.35	0.900	31.5	30.5	17.5	1.25	-	-
21	45.9	9.3	51.9	0.46	3.17	3.63	0.874	32.0	34.0	17.5	1.40	-	-
22	45.9	37.0	84.0	2.74	1.10	3.84	0.286	32.0	31.5	17.5	1.78	-	-
23	45.9	25.3	66.7	1.82	1.94	3.76	0.516	32.0	31.5	17.5	1.62	-	-
24	45.9	39.8	80.6	3.18	0.59	3.77	0.156	31.0	30.8	17.6	1.42	-	-
25	45.9	26.3	65.5	1.71	1.98	3.69	0.537	31.0	30.5	17.5	1.32	-	-
26	45.9	12.7	56.9	0.97	3.06	4.03	0.758	31.5	31.5	17.5	1.48	-	-
27	45.9	7.9	51.8	0.46	3.34	3.80	0.879	31.5	33.0	17.5	1.40	-	-
28	45.9	29.9	64.6	1.83	1.93	3.76	0.513	29.0	28.0	17.2	1.22	2.0	216
29	45.9	27.2	67.8	1.77	1.92	3.69	0.521	26.6	26.5	17.2	1.37	1.7	220
30	45.9	27.1	66.2	1.72	1.94	3.66	0.530	29.0	29.0	17.1	1.51	1.9	237
31	45.9	26.5	67.0	1.77	1.94	3.71	0.523	30.0	30.0	17.1	1.45	2.0	262
32	45.9	24.7	69.2	1.77	1.96	3.73	0.525	30.5	31.0	17.1	1.42	1.9	324
33	45.9	35.7	67.4	1.78	1.88	3.66	0.514	31.0	31.5	17.1	1.62	1.0	328
34	45.9	30.5	67.9	1.75	1.96	3.71	0.525	30.0	32.0	17.1	1.67	4.3	300
35	45.9	26.4	67.6	1.81	1.99	3.80	0.524	31.0	31.5	17.2	1.65	2.5	301
36	45.9	27.8	66.0	1.77	1.96	3.73	0.525	31.0	31.0	17.1	1.70	1.9	292

justed to maintain a constant level. Glacial acetic acid is fed to this reservoir at a predetermined rate from a constant-head acid supply bottle.

The method of feed gas introduction is different in each of the columns. The feed enters the column M1 through a 1.5-mm. I.D. tube which is directed downward near the liquid curtain. In column S3, the feed gas may enter the separating zone through two 6-mm. I.D. tubes sealed perpendicular to the column wall, or it can be mixed with the vapor feed to either the enriching section or the stripping section. In column S5, the feed gas enters the working space through the wall of a short length of porous bronze tube fabricated from 0.031-in. thick Oilite Bronze Strip purchased from the Amplex division of Chrysler Corp. Other lengths of this type of tubing serve as the vapor entry wall for the enriching and stripping sections.

Auxiliary Equipment

Vapor Supply. In the runs made with column M1, the sweep vapor was continuously generated from distilled water in an electrically heated spherical flask (Fig. 10). This boiler was used also during part of

the runs made with column S3, but after run S3-29, and during all the runs made with column S5, the steam was obtained from a 35 lb./sq.in. gage steam supply line, and the flow was controlled manually with a needle valve.

In the runs made with column S3 using ammonia as the sweep vapor, the sweep vapor was generated continuously by passing liquid ammonia through a constant temperature vaporizer coil, reducing the pressure, and passing the vapor through a calibrated orifice into the vapor feed line.

The column vapor feed line is heated electrically, and the heat input is regulated to maintain essentially saturated vapor feed to the column unless otherwise noted in the data. Liquid is withdrawn from the reservoir at the base of the column at a rate sufficient to maintain the reservoir level constant. When steam is used as the sweep vapor, the vapor rate is determined by measuring the quantity of the liquid withdrawn during a run of known length, correcting it for the quantity of vapor present in the product gas streams.

Feed Gas Supply. In the hydrogen-natural gas runs and air runs, the feed gas flows from a compressed gas or compressed air storage cylinder through a pressure

regulating valve to the column feed inlet, and the column pressure is controlled by this valve.

In the smoke runs, the smoke feed is generated by forcing air through a burning cigarette in a pyrex glass apparatus. Two of these "smoke tubes," connected in parallel for alternate use, are installed in the air line to the column. The density of the smoke feed entering the column is controlled by regulating the flow of air through a by-pass around the "smoke tube."

Product Analysis and Metering. When steam is used as the sweep vapor in hydrogen-natural gas separations, water vapor is removed from the product gas streams by allowing each stream to flow through a water jacketed condenser and a dry ice cooled water trap (Fig. 10). When ammonia is used as the sweep vapor, the product streams pass through concentrated sulfuric acid absorption traps, which remove ammonia and water, rather than through the freeze-out traps.

In air runs an Orsat apparatus is used for analyzing the oxygen-nitrogen mixtures, and the accuracy of these analyses is estimated to be ±0.2 mole %.

In hydrogen-natural gas runs, portions of the product streams are diverted through two Gow-Mac thermal conductivity cells for analysis. The cell currents are maintained constant by means of a variable resistor, and a potentiometer and fixed resistor. The thermal conductivity cell analyses are estimated to be accurate to ±0.1 mole %.

The effluent gas streams from the analysis cells are recombined with the respective product streams for flow measurement. A calibrated orifice is provided in each product stream for metering relatively large flow rates, and a wet test meter is connected in series with each orifice for metering small flow rates. The effluent gases from the wet test meters are combined and vented.

TABLE 1b

TABLE 1b
SUMMARY OF EXPERIMENTAL DATA AND RESULTS

Column M1; Air Separations; Steam Sweep Vapor; Water Liquid Curtain

Run No.	Mole % O₂ in Feed	Mole % O₂ in Bottoms	Mole % O₂ in Tops	Bottoms Flow S.C.F.H.	Tops Flow S.C.F.H.	Feed Rate S.C.F.H.	Bottoms Temp. °C.	Tops Temp. °C.	Column Pressure p.s.i.a.	Vapor Consumption lbs./hr.
M1-14	21.0	20.1	21.5	1.268	1.250	2.518	34.3	40.0	17.5	2.55
M1-16	21.0	20.1	21.4	0.1404	0.1192	0.2596	34.0	35.8	17.5	2.44
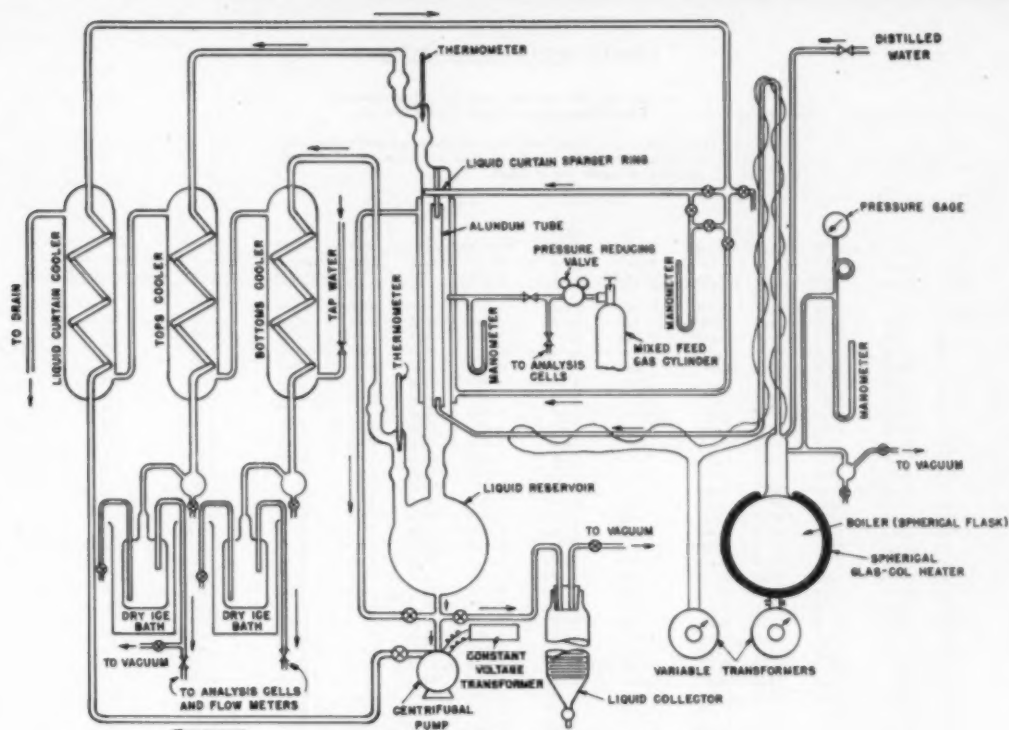
▲ Fig. 10. Column M1 and auxiliary equipment.

Experimental Results

Column M1

Hydrogen-Natural Gas Separations. The separation of hydrogen from hydrogen-natural gas mixtures was investigated with column *M1*, and the results are presented in Table 1a and Figures 13 and 14. The liquid curtain rate was approximately 130 lb./hr. in all runs except runs *M1*-33-35.

Results presented in Figure 13 show the effect of varying the feed gas rate while maintaining all other variables essentially constant (runs *M1*-4, 10, 12, and 23). These results show that the degree of separation $(y_b - y_s)$, which is relatively good at low feed rates, decreases rapidly with increasing feed rate. Results shown in Figure 14 demonstrate the effect on the product compositions of varying the tops-to-feed ratio at two different feed rates while maintaining all other variables essentially constant (runs *M1*-5, 6, 8, 9, 21, and 23-27).

Air Separations. The degree of separation obtained during the two air separation runs with column *M1* (runs *M1*-14 and 15) was smaller than that observed in the hydrogen-natural gas separations because the diffusivities of oxygen and nitrogen through steam are more nearly equal than those of hydrogen and methane. Separations produced an enriched oxygen stream as the overhead product. Comparison of the two runs shows that essentially no change in separation was obtained by decreasing the feed rate from 2.5 S.C.F.H. to 0.26 (Table 1b).

Column S3

Smoke Separations. A series of runs was made to investigate the separation of

Fig. 11. Sweep diffusion column S3.

SUMMARY OF EXPERIMENTAL DATA AND RESULTS

Column S3; Hydrogen-Natural Gas Separations;
Steam Sweep Vapor; Water Liquid Curtain

Runs S3-3 to 10, feed entered through tubes perpendicular
to column wall; in remaining runs on column S3, the feed
entered at upper vapor inlet.

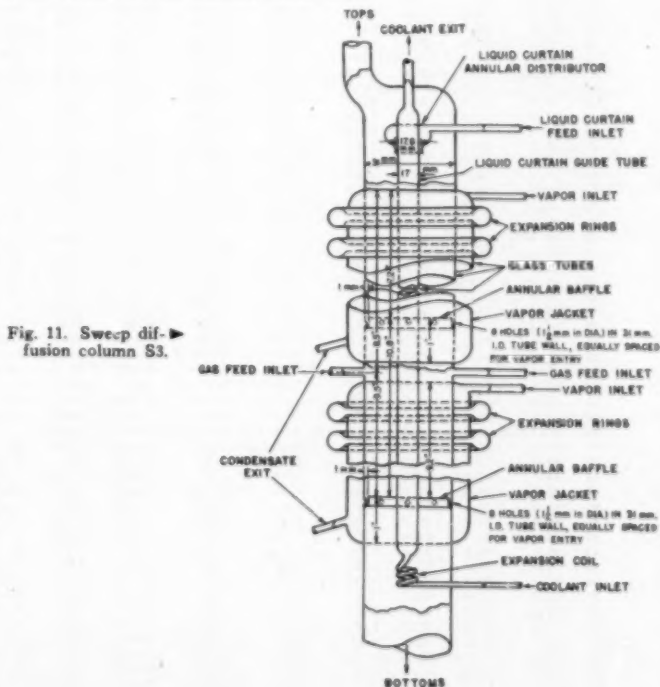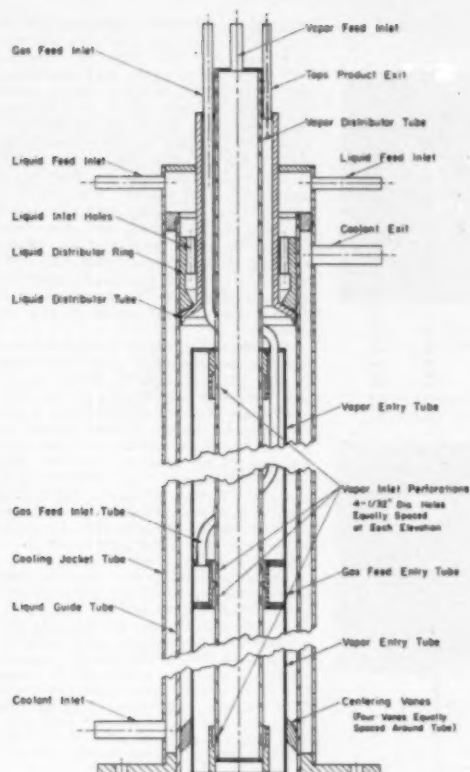| Run No.	Mole % H₂ in Feed	Mole % H₂ in Bottoms	Mole % H₂ in Tops	Bottoms Flow S.C.F.H.	Tops Flow S.C.F.H.	Feed Rate S.C.F.H.	Tops to Feed Ratio	Bottoms Temp. °C.	Tops Temp. °C.	Column Pressure p.s.i.a.	Vapor Consumption lbs./hr.	Liquid Downflow Rate, lbs./hr.
S3- 3	45.9	43.9	47.8	0.321	0.365	0.686	0.532	30.5	32.0	17.6	1.79	1.79
4	45.9	16.8	74.0	0.380	0.417	0.797	0.523	30.0	32.0	17.6	1.65	216
5	45.9	15.7	74.8	0.378	0.419	0.797	0.526	30.6	32.5	17.6	1.58	200
6	45.9	18.6	72.3	0.379	0.412	0.791	0.521	30.5	32.0	17.6	1.60	188
7	45.9	28.2	63.5	1.088	1.173	2.261	0.519	30.0	32.5	17.4	1.76	179
8	45.9	33.0	58.2	1.97	1.99	3.96	0.503	30.0	33.0	17.6	2.03	171
9	45.9	39.2	53.3	3.37	3.00	6.37	0.471	30.0	34.0	17.6	1.93	174
10	45.9	41.3	50.7	4.08	4.38	8.46	0.518	30.0	-	17.7	1.94	171
11	51.6	42.4	60.0	3.92	4.46	8.38	0.532	30.0	37.0	17.6	1.94	185
12	51.6	40.5	61.8	3.07	3.43	6.50	0.528	30.0	33.0	17.6	1.94	185
13	51.6	35.3	67.5	1.90	2.06	3.96	0.520	30.5	31.5	17.6	1.88	182
14	51.6	29.7	72.1	1.06	1.21	2.27	0.533	31.0	31.0	17.7	1.81	182
15	51.6	22.6	75.7	0.467	0.571	1.038	0.550	31.0	31.5	17.6	1.85	182
16	51.6	45.9	57.1	6.10	6.64	12.74	0.521	30.0	42.0	17.8	2.10	182
24	51.6	35.8	67.7	1.589	1.632	3.221	0.506	30.0	32.0	17.9	1.83	157
25	51.6	35.2	68.5	1.598	1.632	3.230	0.505	29.8	31.8	17.9	1.81	185
26	51.6	34.2	69.4	1.660	1.730	3.390	0.510	31.0	33.5	17.9	1.79	213
27	51.6	33.8	69.6	1.599	1.669	3.268	0.510	31.8	34.0	17.9	1.69	177
28	51.6	33.0	70.5	1.545	1.747	3.292	0.530	29.1	30.1	17.9	1.80	209
29	51.6	36.3	67.5	1.545	1.590	3.135	0.507	31.0	31.5	17.9	1.80	91
35	15.0	13.2	25.8	5.07	0.754	5.82	0.130	29.5	32.5	17.6	1.37	204
36	15.0	12.6	27.4	4.97	0.758	5.70	0.130	30.2	31.8	17.7	1.53	203
37	15.0	8.0	22.8	1.74	1.57	3.31	0.475	29.0	33.1	17.5	1.66	205
38	15.0	6.6	16.4	0.898	4.97	5.87	0.846	29.9	33.6	17.5	1.98	204
39	51.6	43.0	73.7	2.75	1.06	3.81	0.278	36.3	33.8	17.6	1.71	196
40	51.6	23.4	59.1	0.829	3.30	4.15	0.799	38.7	33.8	17.6	1.76	196
41	51.6	28.2	62.8	1.20	2.68	3.82	0.685	36.9	33.8	17.6	1.66	200
42	47.2	27.6	68.2	1.550	1.683	3.133	0.506	33.3	35.5	17.6	1.63	442
43	47.2	27.3	68.6	1.533	1.576	3.109	0.507	34.1	36.8	17.6	1.91	547
44	47.2	30.0	66.1	1.627	1.627	3.254	0.500	36.6	36.6	17.6	2.01	161
45	47.2	30.7	65.2	1.642	1.627	3.269	0.498	36.8	37.2	17.6	1.68	156
46	47.2	28.9	67.4	1.679	1.670	3.349	0.499	35.8	38.0	17.6	1.92	507
47	47.2	27.6	69.1	1.530	1.546	3.076	0.503	35.3	36.1	17.6	1.99	422
48	47.2	28.4	68.4	1.588	1.561	3.149	0.496	35.3	36.5	17.6	1.80	547
49	47.2	28.3	68.5	1.596	1.561	3.157	0.495	36.4	38.0	17.6	1.78	243
50	47.2	28.7	68.5	1.679	1.592	3.270	0.488	36.3	36.9	17.6	1.73	319
51	47.2	27.9	67.7	1.528	1.601	3.129	0.512	36.3	37.0	17.6	1.73	315
52	47.2	27.6	68.3	1.528	1.570	3.098	0.506	34.7	36.2	17.5	1.74	457
53	47.2	27.6	67.7	1.510	1.578	3.088	0.511	37.0	37.1	17.5	1.72	512
54	47.2	28.5	67.0	1.578	1.635	3.213	0.509	38.0	37.9	17.5	1.67	246
55	47.2	38.2	56.5	3.84	3.86	7.30	0.801	37.0	39.5	17.5	1.67	148
56	47.2	37.6	57.6	3.56	3.58	7.14	0.501	35.0	38.9	17.5	1.77	243
57	47.2	36.9	58.0	3.53	3.56	7.09	0.502	36.1	41.0	17.5	1.65	294
58	47.2	36.9	58.2	3.52	3.82	7.34	0.520	35.3	40.3	17.7	1.84	214
59	47.2	35.7	59.4	3.43	3.66	7.09	0.516	35.1	41.1	17.6	1.94	282
60	47.2	36.7	59.5	3.51	3.78	7.29	0.518	36.1	41.2	17.6	2.00	333
61	47.2	36.0	60.8	3.46	3.79	7.25	0.523	34.9	41.4	17.6	1.93	467
62	47.2	36.7	59.3	3.51	3.76	7.27	0.518	36.1	42.6	17.6	1.74	402
63	47.2	35.9	59.0	3.45	3.67	7.12	0.515	36.9	42.9	17.5	1.72	487
64	47.2	37.7	57.4	3.57	3.69	7.26	0.509	36.7	40.2	17.6	1.67	547
65	47.2	38.1	57.3	3.47	3.62	7.09	0.511	36.4	38.9	17.6	1.61	267
78	43.4	38.6	48.8	5.00	4.87	9.87	0.494	37.9	46.1	17.5	1.94	188
79	43.4	37.5	50.1	4.99	4.87	9.86	0.495	37.0	47.4	17.4	1.95	222
80	43.4	37.0	50.3	5.01	4.90	9.91	0.495	36.9	48.1	17.4	1.92	342
81	43.4	36.4	50.9	5.00	4.90	9.90	0.495	36.4	48.3	17.4	1.92	433
82	43.4	36.4	50.9	4.92	4.83	9.75	0.495	36.8	48.2	17.4	1.96	518
83	43.4	31.2	56.3	2.38	2.40	4.78	0.502	34.2	38.0	17.5	1.84	172
84	43.4	29.9	57.5	2.35	2.40	4.75	0.505	33.9	38.0	17.5	1.83	297
85	43.4	28.4	59.2	2.33	2.39	4.72	0.507	33.7	38.0	17.5	1.66	398
86	43.4	28.9	58.8	2.33	2.38	4.71	0.506	33.8	37.7	17.5	1.84	506
87	43.4	32.9	54.0	3.50	3.67	7.17	0.512	34.7	43.0	17.3	1.84	412
88	43.4	37.1	50.6	4.98	4.85	9.83	0.493	35.0	47.0	17.5	1.83	411
89	43.4	32.8	54.4	3.53	3.64	7.17	0.506	35.6	44.0	17.5	1.86	436
90	43.4	25.3	63.2	1.654	1.602	3.256	0.493	34.1	35.6	17.6	1.85	418
91	46.0	34.7	57.4	3.45	3.54	7.00	0.506	36.7	40.6	17.6	1.84	371
92	46.0	34.1	57.6	3.54	3.77	7.31	0.516	37.6	41.1	17.7	1.82	422
93	46.0	34.6	57.4	3.58	3.64	7.22	0.505	38.0	41.9	17.8	1.85	418
94	46.0	34.2	57.9	3.56	3.54	7.10	0.499	37.9	41.2	17.7	1.86	418
95	46.0	29.7	62.0	2.36	2.46	4.82	0.510	38.0	37.4	17.6	1.97	361
96	46.0	30.2	62.0	2.36	2.46	4.82	0.510	37.9	38.0	17.3	1.87	455
97	46.0	29.8	62.7	2.42	2.51	4.93	0.510	37.8	38.0	17.4	1.89	520
98	46.0	29.9	62.6	2.42	2.54	4.96	0.512	36.8	38.0	17.4	1.87	358
99	46.0	30.8	61.6	2.31	2.49	4.80	0.519	39.0	37.6	17.3	1.88	202
100	46.0	40.5	52.8	5.12	4.99	10.11	0.494	40.0	45.0	17.7	1.86	148
101	46.0	39.2	53.3	5.14	5.00	10.14	0.493	38.9	47.0	17.6	1.83	315
102	46.0	38.5	54.0	5.12	4.99	10.11	0.494	38.3	47.6	17.7	1.86	451
103	46.0	38.2	54.3	5.07	5.01	10.08	0.497	38.1	47.3	17.7	1.83	510

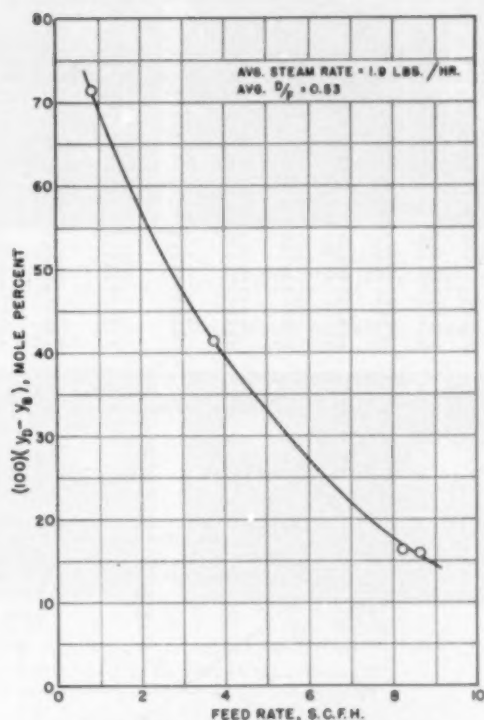Fig. 12. Sectional view of sweep diffusion column S5.

Fig. 13. Hydrogen-natural gas separations.
Effect of feed rate on degree of separation in column M1.

cigarette smoke from air, and the results are shown in Figure 15. The feed was introduced with the vapor at the lower vapor inlet during these runs, and the liquid curtain rate was 200 lb./hr.

Results demonstrate that when no bottom product is withdrawn while the vapor rate is substantial, most of the smoke is removed from the overhead product and apparently remains in the circulating liquid (run S3-32A). Likewise, when the overhead and bottoms products are withdrawn at equal rates, most of the smoke is removed from the overhead product, while a small amount is removed from the bottom product (runs S3-32B and D). When no vapor is introduced, essentially no smoke is removed from either product (run S3-32C).

It was found that, for the conditions of runs S3-32B and D, no change in the degree of separation is apparent when the liquid curtain rate is decreased to zero. This indicates that essentially complete removal of smoke can be effected by a single-stage process.

Hydrogen-Natural Gas Separations

Steam as Vapor (Table 1c). Use of two different types of feed entry means was investigated in runs S3-3 through 16. In runs S3-3 through 10, the feed was introduced perpendicular to the column wall through two diametrically opposite inlet

tubes, located immediately below the upper vapor inlet (Fig. 11). In runs S3-11 through 16, the feed was introduced essentially parallel to the column wall by allowing it to enter with the vapor through the upper vapor inlet. The feed rate was varied with each type of feed entry while all other operating conditions were maintained essentially constant.

Results demonstrate that when the feed is introduced through the inlet which is essentially parallel to the column wall, the separation ($y_b - y_s$) is much better than when it is introduced through the perpendicular inlets. The poor performance of column S3 when the feed enters through the perpendicular inlets is undoubtedly due to mixing of the countercurrent gas streams caused by this method of feed introduction.

As a result of this investigation, the feed gas was introduced with the vapor through the upper vapor inlet in all subsequent runs made with column S3.

The effect of the feed rate on the degree of separation ($y_b - y_s$) was investigated in runs S3-53, 63, 97, and 103, and the results are presented in Figure 16. It should be noted that when the feed is introduced with the vapor through the upper vapor inlet at rates greater than about 5 S.C.F.H., the resulting separations are better than those observed with column M1 for similar operating conditions; however, the performance is poorer than that of column M1 at lower feed rates.

The fact that the performance of column S3 is poorer than that of column M1 at the lower feed gas rates is probably a

TABLE 1d
SUMMARY OF EXPERIMENTAL DATA AND RESULTS

Column S3: Hydrogen-Natural Gas Separations; Ammonia Sweep Vapor;
2.5 wgt.% acetic Acid in Water; Liquid Curtain;
Feed Introduced at Upper Vapor Inlet

Run No.	Mole % H₂ in Feed	Mole % H₂ in Bottoms	Mole % H₂ in Tops	Bottoms Flow S.C.F.H.	Tops Flow S.C.F.H.	Feed Rate S.C.F.H.	Tops to Bottoms Feed Ratio	Tops Temp. °C.	Bottoms Temp. °C.	Vapor Inlet Temp. °C.	Column Pressure p.s.i.a.	Vapor Consumption lbs./hr.	Liquid Curtain Overflow Rate,lb./hr.
S3-104	51.0	21.7	71.6	1.50	1.59	3.09	0.515	27.5	25.2	76	17.6	1.60	151
S3-130	51.0	30.9	71.6	1.67	1.68	3.35	0.503	29.7	25.6	170	17.6	1.90	172

Column S5: Hydrogen-Natural Gas Separations;
Steam Sweep Vapor; Water Liquid Curtain

Run No.	Mole % H₂ in Feed	Mole % H₂ in Bottoms	Mole % H₂ in Tops	Bottoms Flow S.C.F.H.	Tops Flow S.C.F.H.	Feed Rate, S.C.F.H.	Moles Tops per Mole Feed	Column Pressure p-s-i-a.	Vapor Consumption Lbs./Hr.	Effluent Liquid Temp. °F.	Liquid Downflow Rate Lbs./Hr.
S5-1	46.2	0.0-0.3	84.6	0.272	0.346	0.610	0.560	17.6	6.90	73	190
2	46.2	1.0	80.4	1.45	1.97	3.40	0.579	17.7	4.91	73	218
3	46.2	4.7	79.0	1.46	1.97	3.42	0.575	17.7	4.93	73	808
4	46.2	7.4	77.0	1.44	1.91	3.36	0.571	17.7	4.93	72	1006
5	46.2	41.1	50.9	1.62	1.74	3.36	0.520	17.6	4.90	66	5
6	46.2	4.6	87.2	1.75	1.77	3.47	0.510	17.7	4.04	73	210
7	46.2	10.9	98.2	2.07	1.50	3.57	0.420	17.6	4.50	73	210
9	46.2	2.2	87.8	1.75	1.85	3.59	0.514	17.7	5.30	80	196
9	46.2	4.6	88.7	1.75	1.85	3.59	0.510	17.7	5.09	73	810
10	46.2	7.2	85.1	1.77	1.78	3.55	0.502	17.7	5.06	73	945
11	46.2	3.2	87.0	1.75	1.83	3.58	0.511	17.7	5.07	73	220
12	46.2	7.4	85.0	1.77	1.78	3.55	0.502	17.7	5.06	96	90
13	46.2	14.3	76.2	3.44	3.62	7.06	0.511	17.7	4.98	79	199
14	46.2	7.2	80.5	3.54	3.62	7.16	0.534	17.9	5.38	73	515
15	46.2	5.9	79.1	3.36	3.78	7.14	0.530	17.9	5.11	73	955
16	46.2	26.3	66.2	3.52	3.62	7.14	0.507	18.1	2.86	73	211
17	46.2	15.3	77.4	1.75	1.79	3.54	0.506	18.1	2.80	73	211
18	46.2	0.7-1.1	87.9	1.76	1.91	3.67	0.521	18.1	3.22	80	217
19	46.2	34.6	58.2	3.60	3.51	7.11	0.494	18.0	3.00	90	217
20	46.2	32.6	62.1	3.61	3.21	6.82	0.471	18.0	6.00	80	214
21	46.2	14.0	78.3	3.49	3.45	6.92	0.496	17.9	9.33	96	209
22	46.2	45.0	47.4	3.62	3.59	7.21	0.498	17.9	5.58	93	5.6
23	46.2	35.8	99.36	7.67	0.306	8.58	0.106	17.9	5.36	61	22.3
24	46.2	6.1	85.0	1.81	1.80	3.61	0.499	29.6	4.88	77	214

¹ The column was realigned after run S5-7 so that the liquid distribution was more uniform.

² The feed gas entered the bottom of the column in runs S5-9-12, 20, and 23. It entered between the upper and lower separating sections in all other runs.
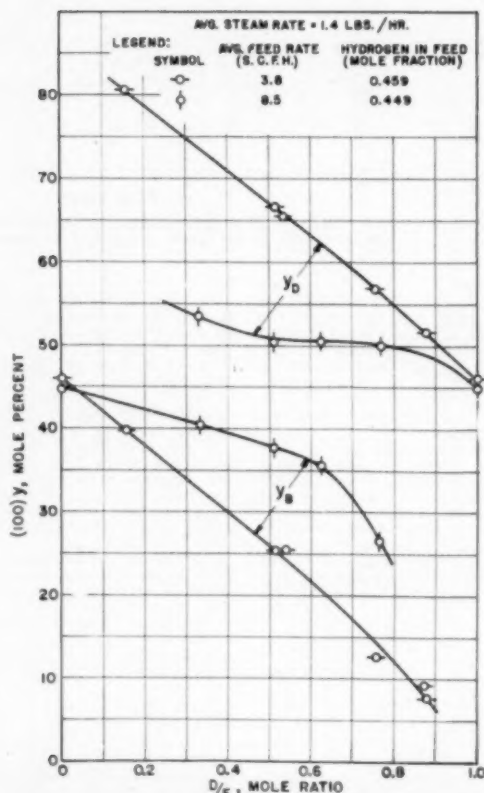
Fig. 14. Hydrogen-natural gas separations.
Effect of tops to feed ratio on product compositions in column M1.

result of the different method employed for introducing vapor into the separating zone of column S3. The vapor is introduced only at the bottom of the enriching section and at the bottom of the stripping section in column S3, whereas it is introduced throughout the length of column M1. Therefore, although the dimensions of the columns are the same, the effective length of column S3 is probably less than that of column M1. The superior performance of column S3 at the higher feed rates, when the feed is introduced with the vapor through the upper vapor inlet, is probably a result of the more efficient feed entry means. (It should be recalled that the feed entered column M1 through a single, downwardly directed nozzle in the annulus).

The effect of the liquid curtain downflow rate was investigated at several feed rates in runs S3-24 through 29, 42 through 65, and 78 through 103. Results of this investigation are presented graphically in Figure 17. Data for Figure 17 were selected so that the maximum variation in the vapor rate for all the points is less than 10%, and so that the maximum variation in the feed rate for each series of constant-feed-rate points is less than 5%. At each feed rate investigated, the separation $(y_D - y_B)$ increases as the liquid curtain rate is increased; however, at the lower feed rates, an optimum liquid rate is reached, above which increasing liquid rate does not appreciably change the separation.

The effect of the tops-to-feed mole ratio on the column performance was investigated in runs S3-13, 39, 40, and 41, and the results are presented graphically in Figure 18. These results agree qualitatively with those obtained with column M1; however, the separations $(y_D - y_B)$ are only about three fourths as great as those obtained with column M1 under similar operating conditions.

Ammonia as Vapor (Table 1d). Ammonia was used as the sweep vapor in runs S3-104 and 105 in order to obtain data showing the extent to which thermal diffusion affects sweep diffusion separations. Operating conditions were adjusted to reproduce those used in runs S3-25 and 27, except for the temperature of the vapor feed, and the comparative results are presented in Table 2. The room temperature ammonia run (run S3-104) yielded better separation than that observed in the steam runs, and the separation was improved somewhat when the vapor temperature was increased (run S3-105).

Column S5

Hydrogen-Natural Gas Separations. The separation of hydrogen-natural gas mixtures was investigated with column S5, and the results are presented in Table 1e and Figures 19-21.

The degree of separation was found to go through a maximum as the liquid curtain rate was increased at two different feed rates while all other variables were maintained essentially constant (runs S5-5, 8-15, and 22; Fig. 19).

Results presented in Figure 20 show the effect on the degree of separation of varying the sweep vapor rate at two different feed rates, while maintaining all other variables essentially constant (runs S5-6, 8, 11, 13, 16-18, and 21). The effect of the feed rate on the degree of separation is also indicated in Figure 21 in which the separation is shown as a function of the feed rate at several constant vapor rates (runs S5-8, 11, 13, 16-18, and 21).

Comparison of Theory and Experiment

Calculation Procedure

There are several ways in which the developed theory may be compared to the observed results. It was found useful, for example, to compare the length of column theoretically required to give the observed separation to the actual column length. The ratio obtained, ϵ, is called the column efficiency, and is analogous to the over-all plate efficiency of distillation. This procedure permits rational design of commercial scale columns from data obtained on bench-scale equipment. It was found desirable also, in certain cases, to compare the predicted product compositions to the observed product compositions. In either case it is necessary first to evaluate the appropriate quantities appearing in Equations (61)-(66) and (61s)-(66s), and then to solve for the unknown value. The procedure followed for the enriching section is to evaluate in turn, N_o, D_{12}, D_{02}, D_{0s}, α_{12}^*, α_{01}^*, α_{02}^*, s from Equation (20), $\overline{P-p_0}$ by (19), p_0 from (21), K_4 from (23), Re_t from (41), U from (43) or (45), m' for parallel planes from Figure 7, m for curved surfaces from Figure 7 and Equation (68), E^H for curved surfaces from (69) or (70), L from (40), H_S from (32), H_T from (57), H from (56), K_o from (33), K from (54), n from (59), and finally either Z_o or y_D from the appropriate equations in the group from (61) to (66), where one of these quantities is the observed value and the other the predicted value. A similar procedure is followed for the stripping section.

Effect of Longitudinal Diffusion and Thermal Diffusion

To determine magnitude of the predicted effects of longitudinal diffusion and thermal diffusion, several calculations were made using the data of a typical hydrogen-natural gas run on column $M1$, wherein terms relating to longitudinal diffusion (K_4) and thermal diffusion (H_T) were alternately included and set equal to zero. It was assumed that the natural gas was pure methane. In the evaluation of the thermal diffusion constants, a value of 8 was chosen as the exponent relating the force between molecules and their distance from each other. From Jones and Furry (6), R_T is then 0.366, and the thermal diffusion constants are readily calculated.

Product compositions predicted for the various cases are given in Table 3. Under the conditions of this run, longitudinal diffusion affects the predicted separation by less than 1%. This would normally be the case in sweep diffusion columns, and
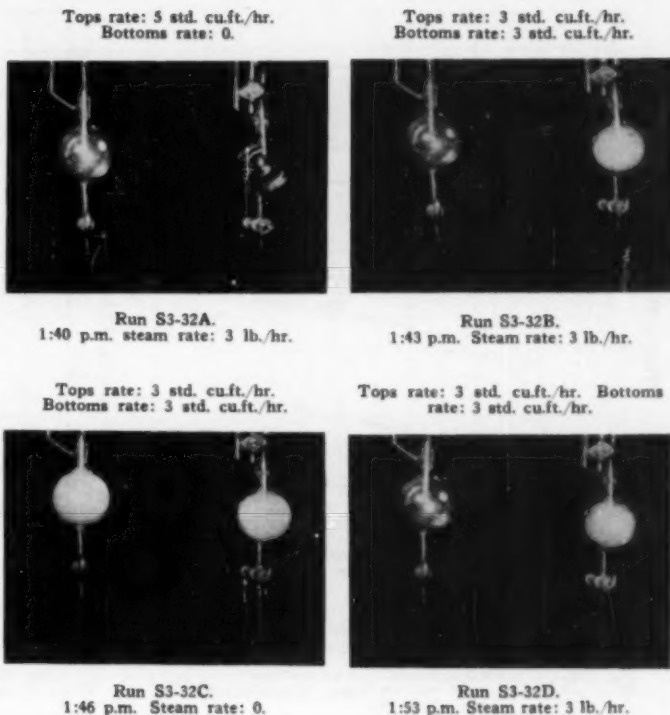

Tops rate: 5 std. cu.ft./hr.
Bottoms rate: 0.

Run S3-32A.
1:40 p.m. steam rate: 3 lb./hr.

Tops rate: 3 std. cu.ft./hr.
Bottoms rate: 3 std. cu.ft./hr.

Run S3-32B.
1:43 p.m. Steam rate: 3 lb./hr.

Tops rate: 3 std. cu.ft./hr.
Bottoms rate: 3 std. cu.ft./hr.

Run S3-32C.
1:46 p.m. Steam rate: 0.

Tops rate: 3 std. cu.ft./hr. Bottoms rate: 3 std. cu.ft./hr.

Run S3-32D.
1:53 p.m. Steam rate: 3 lb./hr.

Fig. 15. Separation of smoke from air with column S3.

the K_4 term would become important only if f_L is considerably less than 10^{-6} g.moles/(cm.)(sec.).

Table 3 also shows that the theory predicts an improvement in separation due to thermal diffusion of about 5% when

$\Delta T/\overline{T} = 0.22$. If both thermal diffusion and longitudinal diffusion terms are set equal to zero, a slight compensating effect is evident.

Although column $S3$ did not meet the design conditions of a theoretical sweep

Fig. 16. Hydrogen ▶ natural gas separations. Effect of feed rate on degree of separation in column S3.
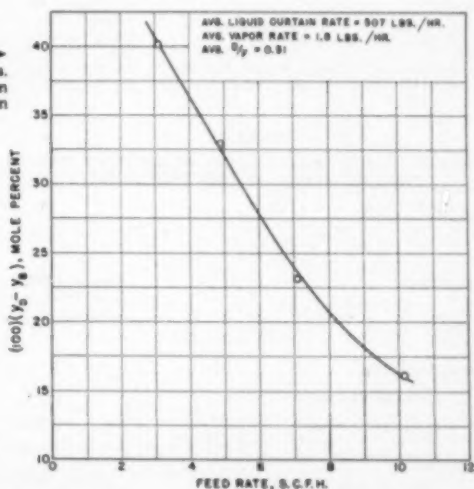
TABLE 2

EFFECT OF CHANGING THE SWEEP VAPOR AND VARYING THE VAPOR TEMPERATURE IN COLUMN S3

Hydrogen-Natural Gas Separations

Run No.	Vapor Inlet Temp. °F.	Sweep Vapor	Vapor Rate lb.Moles/Hr.	Feed Rate S.C.F.H.	Separation 100 (y_D-y_B) Mole%
S3- 26	222	Steam	0.1006	3.23	33.3
27	222	Steam	0.1050	3.27	35.8
104	74	Ammonia	0.0894	3.09	39.8
105	178	Ammonia	0.1000	3.35	41.8

Fig. 17. Hydrogen-natural gas separations.
Effect of liquid curtain rate on degree of separation
in column S3.

Fig. 18. Hydrogen-natural gas separations.
Effect of tops to feed ratio on product compositions
in column S3.

diffusion column in that the vapor was not equally distributed along the column, the runs using ammonia to separate hydrogen from natural gas showed an increase in separation of just 5% when the ammonia entry temperature was raised from 74° to 174° F.; i.e., $\Delta T/\overline{T} = 0.17$. Since the diffusion properties of ammonia are much like steam, this result is a rough check of the theoretically predicted thermal diffusion effect.

Evaluation of Column Efficiency

The column efficiency, ϵ, was calculated for several runs made on columns $M1$ and $S5$, and the results are tabulated in Table 4. Perhaps the most striking experiments supporting the theory are the runs on air, where oxygen, though higher in molecular weight, diffuses through steam more rapidly than nitrogen because of its smaller molecular diameter and as a result is enriched in the top stream, as predicted by theory. The separation obtained could have been achieved in about 58% of the length of column $M1$ for a theoretically perfect column. The over-all column efficiency, ϵ, did not change with feed rate in the air runs. Thus, the experimental results and the theory agree in that the separation is not improved by lowering the feed rate.

Using the distillation analogy, the conditions of both air runs are such that the 18-in. long column corresponds to less than two theoretical plates, and the reflux rate is adequately high in the high feed rate run so that increasing the reflux ratio (by lowering the feed rate) has a small effect on the separation obtained. To improve the separation, it is necessary to use a longer column or a higher vapor rate.

In the hydrogen-natural gas runs, the values of ϵ for $M1$-4 and $M1$-31 show the effect of the inefficient method of feed introduction into column $M1$. The flow of feed gas through the small downwardly directed feed inlet tube in column $M1$ un-

TABLE 3

PREDICTED EFFECT OF THERMAL DIFFUSION AND LONGITUDINAL DIFFUSION
ON GAS SEPARATION IN THE SWEEP DIFFUSION PROCESS

Run Number	$M1$-31
$100y_F$:	45.9
$100y_D$ Predicted:	
All Terms Included	73.8
K_d Set Equal to Zero	74.0
K_z Set Equal to Zero	72.5
Both K_d and K_z Set Equal to Zero	72.7

TABLE 4

COLUMN EFFICIENCY FOR SEVERAL EXPERIMENTAL RUNS

Run No.	Feed Gas	Feed Rate S.C.F.H.	Vapor to Feed Ratio #/S.C.F.	Column Pressure p.s.i.a.	Liquid Curtain Reynolds No., Rez	Separation $100(y_D-y_B)$ Mole %	Per Cent Column Efficiency $100 \epsilon_z$
M1-14	Air	2.212	1.01	17.6	1,120	1.4	57
M1-15	Air	0.2896	10.16	17.6	1,110	1.3	58
M1- 4	H₂-Nat. Gas	0.421	2.18	17.6	980	71.4	72
M1-31	H₂-Nat. Gas	3.71	0.39	17.1	860	40.5	34
S5- 9	H₂-Nat. Gas	3.59	1.41	17.7	1,406	81.9	119
S5-10	H₂-Nat. Gas	3.55	1.45	17.7	2,540	77.9	105
S5-11	H₂-Nat. Gas	3.68	1.42	17.7	829	86.1	88
S6-14	H₂-Nat. Gas	7.16	.73	17.9	1,420	73.3	94
S5-17	H₂-Nat. Gas	3.54	.79	18.1	566	62.1	57
S5-23	H₂-Nat. Gas	3.59	.63	17.9	635	80.6	85
S5-24	H₂-Nat. Gas	3.61	1.34	29.6	604	89.0	104

◀ Fig. 19. Hydro-
gen-natural gas
separations.

Effect of liquid
curtain rate on de-
gree of separation
in column S5.

▲ Fig. 20. Hydrogen-natural gas
separations.

Effect of vapor rate on degree of
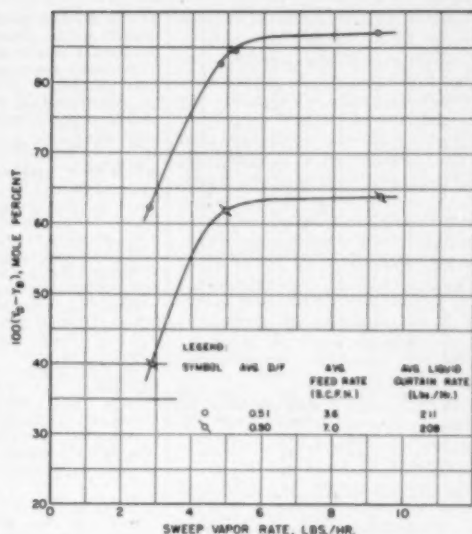separation in column S5.

TABLE 5

EFFECT OF $n_b H_0$ ON THE AREA REQUIRED AND HEPTANE VAPOR
CONSUMPTION FOR CARBON 13 PRODUCTION

$(n_b H_0)$ (10^5) g.-Moles/Sec.-Cm.	Area Required, A_b Sq. Meters	Vapor Consumption, $A_b H_0$ g.-Moles/Sec.
0.3	3000	180
0.5	1820	162.0
0.55	1670	161.7
0.6	1358	162.6
1.0	980	192
1.5	815	228
2.0	1090	435
3.0	1045	1180

TABLE 6

EFFECT OF SWEEP VAPOR ON MOLES OF VAPOR AND AREA OF PLANT REQUIRED
TO SEPARATE A MIXTURE OF $C^{12}H_4$ and $C^{13}H_4$ IN AN IDEAL TAPERED PLANT
DESIGNED FOR MINIMUM VAPOR CONSUMPTION

Ratio of Moles of Vapor Required to Moles of Steam Required for Same Separation		Ratio of Area Required Using a Given Vapor to the Area Required Using Steam, for the Same Separation and Same Annular Distance
1.00	Steam	1.00
0.33	Mercury	0.28
0.31	Carbon Tetrachloride	1.03
0.29	Heptane	1.06
0.23	Perfluoro-n-heptane	1.95

doubtedly caused turbulence and channel-
ing of the gas near the inlet point, and
this shows up in the low value for e_t in
run $M1$-31. At the low feed rate of run
$M1$-4, the effects of turbulence and chan-
neling were less and the column efficiency
was found to be 72%.

The figures in Table 4, applying to ap-
paratus $S5$, reveal that this apparatus con-
formed much more closely to a theoretically
ideal column than did column $M1$. Except
for run $S5$-17, wherein the vapor rate is
about one half its values in the other runs,
the column efficiency averaged 100% with
a maximum deviation of 19% and an
average deviation of 10%. In these runs
there was a 2.4-fold variation in feed rate,
a 1.7-fold variation in column pressure, and
a 4.5-fold variation in liquid curtain Rey-
nolds number. In the low vapor rate run
($S5$-17) the low efficiency obtained may
have resulted from poor vapor distribution
caused by the condensate closing up the
pores in the lower portions of the vapor
entry tubes. At the higher vapor rates the
pressure drop across the porous tubes is
apparently adequate to ensure even vapor
distribution.

The steam flux rate in the high efficiency
runs was approximately at the value corre-
sponding to minimum energy consumption,
as predicted by theory. In design work, the
higher vapor rate should therefore be used,
and under these conditions, the results of
Table 4 indicate that the theory may be
applied with engineering accuracy to the
design of sweep diffusion columns having
mechanical features similar to those of
column $S5$.

Application to Design

The developed theory of sweep diffusion
will be used hereinafter to predict the
vapor consumption and the surface area
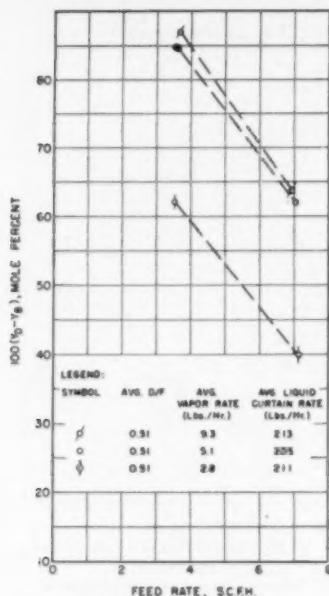required to perform two sample separa-

Fig. 21. Hydrogen-natural gas separations.

Effect of feed rate on degree of separation in column S5.

tions. Because of its treatment by Benedict (1) the separation of $C^{13}H_4$ from $C^{12}H_4$ is a convenient problem for study. The second separation that will be considered is the removal of a portion of the hydrogen from a hydrogen-hydrocarbon gas stream. For these calculations, the small effects of thermal diffusion and longitudinal diffusion have been neglected.

Isotopic Separation of $C^{13}H_4$ from $C^{12}H_4$

It is desired to determine the vapor and surface area requirements for the production of 100 g./day of C^{13} at a concentration of 90 atom % in 50% yield from natural carbon in methane containing 1.06 atom % C^{13}. The more diffusible component of the gas is the $C^{12}H_4$ portion, and therefore values of y will refer to this component. By material balances, $y_F = 0.9894$, $y_D = 0.9947$, $y_B = 0.1$, $D = 0.0167$ g.moles/sec., and $B = 0.0000990$ g.moles/sec.

Process	Separation Factor, α	Number of Units or Area	Power Required, kw, or Chemicals Required
Chemical Exchange	1.013	1000 plates	2 tons NaOH, 3 tons H_2SO_4/day
Thermal Diffusion	1.0027	24,080 sq. meters	75,900 kw.
Centrifuge	1.0195	19,000 centrifuges	?
Gaseous Effusion	1.043	345 stages	140 kw.
Sweep Diffusion (Using Heptane as Vapor)	1.021	1,470 sq. meters	28,000 lbs. steam/hr.(7,800 kw.)

In the first calculation, exhaust steam is used as the sweep vapor. The plant is operated at one atmosphere pressure, and the steam enters at 221° F. and condenses at 95° F.

Equation (12) was used to calculate the diffusivities, wherein

$$V_1^{1/3} = 3.10 \qquad 1/M_1 = 0.0624$$
$$V_2^{1/3} = 3.10 \qquad 1/M_2 = 0.0587$$
$$V_3^{1/3} = 2.66 \qquad 1/M_3 = 0.0555$$
$$P = 1 \text{ atm.} \qquad T = 343° \text{ K.}$$

from which $D_{12} = 0.248$, $D_{13} = 0.2833$, $D_{23} = 0.2788$, and $(D_{13} - D_{23}) = 0.00447$. A plot of Φ vs. $x_b N_o$ reveals a minimum value of 11,950 at $x_b N_o = 2.08 \times 10^{-6}$ g. moles/(sec.) (cm.). Choosing for the minimum practical diffusional distance the value 0.5 cm., one obtains $N_o = 4.16 \times 10^{-6}$ g. moles/(sec.) (cm.). Substituting this and the data presented above for product compositions and rates into Equation (90) yields $A_t = 1,390 \times 10^4$ sq.cm. The steam required is simply $A_t N_o$ which is 578 g. moles/sec., or 82,500 lb./hr. These figures apply to a design based on the minimum vapor requirement using steam.

Use of Vapors Other Than Steam. If a vapor is used with a higher molecular weight and a lower latent heat of vaporization, the power requirements should be less than when steam is used. A calculation was made using heptane as the sweep vapor. The condensing temperature was assumed to be 95° F., $V_3^{1/3} = 5.45$, $1/M_3 = 0.0100$, $T = 343°$ K., $P = 1$ atm., $D_{12} = 0.248$, $D_{13} = 0.1010$, $D_{23} = 0.0984$. Values of A_t, and $A_t N_o$ are shown in Table 5 for various assumed values of $x_b N_o$. Selecting the value of $x_b N_o$ corresponding to minimum vapor consumption, as was done for the calculation where steam was used for the calculation, it is apparent that A_t is 1470 sq.m. as compared to 1390 for steam, a small increase. The vapor consumption is reduced from 578 g. moles/sec. of steam to 162 g. moles/sec. of heptane. The power required to generate the heptane vapor at this rate from the liquid phase at 95° F. is equal to $(\Delta h) A_t N_o = (11,500) (162) (3600)/(252) = 26.6 \times 10^6$ B.t.u./hr. or 7,800 kw., where Δh is the enthalpy change per gram mole of heptane. Using low pressure steam to generate the heptane vapor would require $(26.6) (10^6)/950 = 28,000$ lb./hr. of steam, which is considerably less than the 82,500 lb./hr. required when steam itself is used as the sweep vapor. By similar methods, figures were obtained for the total area and energy requirements for this separation if the sweep vapor were mercury, carbon tetrachloride, and perfluoro-n-heptane. In each case, the calculation was made at the value of $x_b N_o$ corresponding to minimum

vapor consumption. The results of the calculation are shown in Table 6. Apparently, heavy vapor molecules reduce the total area and the moles of vapor required, provided the size of the vapor molecule is not too great. The calculation for perfluoro-n-heptane shows that for large heavy molecules, the greater area of plant required more than overshadows the small improvement in vapor requirements.

Characteristics of the Isotope Separation Plant. Selecting heptane as the sweep vapor, further calculations yield information regarding the separation factor, α, the height equivalent to a theoretical plate, H_t, the total length of plant required, the number of tubes in parallel at various points in the plant and similar data.

Substituting the value $x_b N_o = 0.55 \times 10^{-5}$ g. moles/(sec.) (cm.) into Equation (74) yields $\alpha = 1.021$. In obtaining the optimum $x_b N_o$, at which the vapor consumption is a minimum, Ψ was found to be 3,340 at $(x_b N_o)' = 0.55 \times 10^{-5}$ g. moles/(sec.) (cm.). Next, a value of f_L equal to 1.3×10^{-5} g. moles/(sec.) (cm.) is selected, based on laboratory experience. Equation (95) then yields $H_t = 16.5$ cm. The height of the enriching section, Z_e, is calculated from Equation (94), substituting for y the value $y_D = 0.9947$. The result is $Z_e = 1,125$ cm. or 37 ft. A similar calculation using Equation (94s) yields $Z_s = 10,880$ cm. or 356 ft. The total plant height is therefore 393 ft. This can conveniently be divided into 10 stripping sections, each 36 ft. long, connected together in series, and one enriching section of 36-ft. length. Each section consists of a certain number of tubes connected in parallel. Carbon 13-enriched product is withdrawn from the bottom of the last stripping section, and Carbon 13-impoverished waste is withdrawn from the top of the enriching section. Feed is introduced into one of the lines connecting the bottom of the enriching section to the top of the stripping section.

The width, E, at any elevation, z, is calculated from Equations (84) and (84s), combined respectively with (94) and (94s). A plot of E vs. z starts at zero at the product end of the stripper increases almost linearly at first and then much more rapidly until a maximum value is achieved at the feed point, at which point the curve breaks sharply and reduces almost linearly in the enricher until it reaches zero at the top of the enriching section. The ideal tapered plant represented by this curve may be approximated by a "stepped" plant by dividing the stripper into 10 untapered sections of equal length, and letting the enricher be a simple untapered section. The total vapor entry surface, A_t, for the "stepped" plant should be somewhat greater than for the ideal tapered plant to allow for slight inefficiencies introduced by the fact that L does not equal $2L$ at all elevations. For the stepped Carbon 13 plant, if the unit of construction is a column 36 ft. long having an annular working space with a mean diameter of 2.2 in., approximately 850 of such columns would be required for the plant, of which 275 are connected in parallel in the enriching section, 275 in the first section of the stripper below the feed, and the rest divided in decreasing number among the remaining nine sections of the stripper. The last section of the stripper requires only one of these columns. In the other sections, the columns are connected together in parallel in the manner of vertical-tube heat exchangers.

Comparison with Other Methods of Isotope Separation. Table 7 shows the separation factor, plant size, and power requirements of other processes compared with sweep diffusion for the isotope separation problem just given. Data for the other processes are taken from Benedict's article (1).

The advantage sweep diffusion has over thermal diffusion is almost twenty-fold in size and tenfold in power requirement. Because of the considerably lower energy requirement of gaseous effusion, it is more economical than sweep diffusion for large-scale processes. In the example problem considered, however, the large number of separate stages and the equipment requirements of the gaseous effusion process results in an excessive first cost compared with sweep diffusion, and the latter is the preferred process.

Removal of Hydrogen from a Hydrogen-Hydrocarbon Gas Mixture

In refinery operations, it is sometimes desirable to recover a relatively pure hydrogen stream from a hydrogen-hydrocarbon gas mixture. The section that follows will treat the problem wherein it is desired to remove 50% of the hydrogen in 90 mole % purity from 10,000,000 std. cu.ft./day of a hydrogen-methane mixture containing hydrogen in 50 mole % purity. A material balance over the column yields $y_F = 0.500$, $y_D = 0.900$, $y_B = 0.346$. Converting standard cubic feet per day (at 1 atm. and 32° F.) to g. moles/sec. yields $F = 146.2$, $D = 40.7$, and $B = 105.5$ g. moles/sec. As in the isotope separation problem, it is assumed that x_b equals 0.5 cm. The value of f_L is set at 3×10^{-6} g. moles/(sec.) (cm.).

Since the separation is relatively rough, and the rate of diffusion of hydrogen is much higher than that of methane, this separation can be performed in an untapered plant. For correct design based on theory, it would be proper to choose different values of N_o at several assumed values of E to determine what combination produces the most economical design. Several shortcuts can be applied, however, based on the theory of the tapered plant. In the first place, a reasonable value of E for the column is about 1.75 times the minimum value calculated at the feed point. Likewise, by selecting a vapor rate which results in a minimum value for Φ, the resulting design will be near that corresponding to minimum vapor consumption. This procedure was applied to the hydrogen-methane problem described above. Longitudinal diffusion (K_d) and thermal diffusion (H_t) were neglected. Steam was selected as the sweep vapor, entering at 212° F. and condensing at 95° F. The pressure was set at 1 atm., $T = 341°$ K., $D_{sa} = 1.11$, $D_{ss} = 0.304$, and $D_{ab} = 0.807$. By trial-and-error calculations at various values of x_bN_o it is found that the minimum value for Φ is 1.74, and that it occurs at $x_bN_o = 3 \times 10^{-6}$ g. moles/(sec.) (cm.). This sets the vapor flow per unit area at 6×10^{-6} g. moles/ (sec.) (sq.cm.). Equation (20) is used to calculate s for the enricher and the stripper, using the appropriate $\bar{y}$ in each case. Equations (19) and (21) are then applied separately to the enricher and the stripper to calculate ρ_o and $F - \rho_o$.

It is apparent that these values will differ in the two sections because the hydrogen concentration is higher in the enricher than in the stripper, and as a result, the average

vapor composition in the enricher is less than in the stripper, for a larger driving force is required in the stripper to give the same vapor flow per unit area. Since it is desirable to perform the enriching and stripping operations in a single length of column with one continuous liquid curtain, a single value of L may be used in both sections. Equation (74) yields $a = 2.73$ and $\ln a = 1.003$. Replacing the coefficient 2 by 1.75 in Equation (87) permits evaluation of V in the stripper, yielding $V = 113.2$ g. moles/sec. Adding this to B yields 218.7, the value of L for the stripper. This value is satisfactory as an approximation for the enricher also. The respective values for H_s in the enricher and stripper are calculated from Equation (32) and its analogue for the stripper; E is calculated by dividing L by f_L; the values for K_v are obtained from Equation (33) and its analogue for the stripper; n is calculated from (59) and (59s); and finally Z_o is obtained from Equations (61) and (62), and Z_s from (63s). The results are: $E = 730,000$ cm., $Z_o = 15.6$ cm., $Z_s = 4.6$ cm., $Z_t = 20.2$ cm., and $A_s = Z_tE = 1,480$ sq.cm. or 15,900 sq.ft. If each tube has a separating zone with an average diameter of 2.2 in., 41,500 tubes, each having a vapor entry surface 8 in. long, would be required. The steam requirements are $A_tN_o = 886$ g. moles/sec., or 127,000 lb./hr. of exhaust steam. Because of the short stripping section, feed could be introduced at the bottom of this unit for the sake of mechanical simplicity, adding some extra length to allow for the mixing inefficiency that results. The separation plant could conveniently consist of 21 identical units operating in parallel, each unit containing approximately 2,000 tubes connected together in a tube bundle.

The squatness of this plant is a limitation imposed by the liquid curtain rate above which exploratory experiments have indicated that gas eddy frequency becomes appreciable. To increase the product rate per tube, at a given composition, the tube must be lengthened and the gas reflux rate must be increased. This latter requirement cannot be satisfied by simply increasing the liquid curtain rate because of the poor separating efficiency caused by gas eddies, and, at high rates, because of general gas turbulence. However, at a constant liquid curtain rate, doubling the operating pressure approximately doubles the mass downflow rate of gas per unit width of separating space. The developed theory shows that as pressure is increased, the product rate per tube and the required tube length are increased almost proportionately while the area and vapor requirements remain about the same. A limitation on the pressure exists at the value where the Reynolds number of the gas exceeds its critical value and general turbulence results.

In the hydrogen-hydrocarbon gas separation just discussed, operation at 10 atm. (provided gas turbulence does not occur) would require 1,360 sq.m. or 17,600 sq.ft. of area, 140,000 lb./hr. of steam, and 4,440 tubes of 2.2-in. average diameter and 6.9-ft. length.

Conclusions

The sweep diffusion process is a continuous, differential column-type gas separation process that is capable of separating in the gaseous phase the components of a gas mixture to as high a purity as is desired. Experimental data obtained on laboratory sweep diffusion

columns of several designs demonstrate the efficacy of the process for separating gas mixtures, and for removing suspended solid or liquid particles from a gas stream. The developed theory of the process is useful in (1) analysis of data obtained on laboratory columns to locate sources of inefficiencies, and (2) design of large-scale sweep diffusion plants.

Because the sweep diffusion process is thermodynamically irreversible, it is characterized by a relatively large energy requirement, and its commercialization is therefore probably limited to gas separations that cannot easily be performed by the more standard processes of distillation, absorption, and adsorption. On the other hand, for gas mixtures which contain components having low liquefaction temperatures (such as hydrogen), or for which the separation factor for distillation or absorption is poor (such as isotope separation), or wherein a great number of discrete separations would ordinarily be performed (such as in the purification of synthesis gas from pulverized coal), it is likely that the sweep diffusion process will be economically attractive. Commercial sweep diffusion plants, compared with liquefaction-rectification plants, would be characterized by a low first cost and a high requirement of low quality energy such as exhaust steam.

Notation

Notation for this article was run with Part I, February issue.

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THE END

(Presented at Minneapolis (Minn.) Meeting.)

PRODUCTION OF ETHYLENE BY AUTOTHERMIC CRACKING

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Autothermic cracking is the name given to processes in which the endothermic heat of cracking is offset by introducing air or oxygen with the feed so that the over-all reaction is self-sustaining.

Consideration of the balance between the heat requirements of cracking and those liberated in combustion reactions leads to definition of the thermochemical efficiency of the practical process as the ratio:

$$\frac{\text{heat absorbed by cracking reactions}}{\text{heat evolved by combustion reactions}}$$

By the proper design and use of heat exchange between product and feeds to the reactor this efficiency is raised and dilution of cracked products with nitrogen and carbon oxides is minimized.

From pilot plant studies of the process, yields and product distribution obtained when varying ratios of air to hydrocarbon are employed, are presented and discussed for processing propane or ethane to make ethylene.

Consideration is given to full-scale design based on this work; the process is operable at higher conversions and less recycle than tubular pyrolysis. Yields from ethane range from 75 to 85% in the practical operating range; dilute feeds containing as much as 50% methane can be used satisfactorily. A given plant can operate efficiently over a wide range of feed composition and operating conditions, but the particular choice of conditions will be governed chiefly by local factors.

THE broad idea of autothermic cracking in one form or other is not new, but reconsideration and redevelopment of it starting from first principles has led to processes which are different from former applications of the concept. Some of its practical advantages and disadvantages are obvious. The heat is generated in situ so that high temperatures and pressures can be reached in simple insulated reactors without having to transfer heat through the reactor wall. And by the use of higher temperatures, shorter residence time and smaller reactors are possible. On the other hand, unless pure oxygen is used, the products of reaction are diluted with nitrogen. The dilution with gaseous products of combustion is of less significance but cannot be ignored.

From the scientific rather than the technologic viewpoint, the autothermic technique can be looked on as inverted combustion and the results are of interest in extending the knowledge of combustion where the fuel instead of air is in large excess.

It is obvious that there is a wide range of autothermic processes both catalytic and noncatalytic, such as the cracking of heavy liquid fuels to make gasoline or other distillates, for gas making, the production of acetylene and so forth. This paper is concerned only with the application of the autothermic process to ethylene production.

Production of ethylene from ethane and oxygen was carried out in Germany during the last war (1). The German process was carried out at about 0.5 atm. abs., and for this reason coupled with the use of oxygen, did not appear very attractive. Early in this experimental work it was found, however, that there did not seem to be any real need for such low pressures, and that with appropriate attention to heat exchange and thermal economy the justification for using oxygen rather than air receded.

As is known from conventional tubular thermal cracking processes a wide range of hydrocarbon stocks can be cracked to give substantial yields of ethylene; in general the lower the

molecular weight of the feed stock the higher the yield possible, but also the severer the conditions required of time and temperature, particularly the latter. Thus with propane, when for example, 50% conversion is obtained by heating for about one-half second at 1400-1425° F., there is obtained 0.57 moles of ethylene, 0.15 moles of ethane, and 0.30 moles of propylene/mole of propane reacted (2). With ethane more severe conditions are required for the same conversion yielding 0.88 moles of ethylene/mole of ethane reacted. Ultimate yields of course depend on conversion level and the extent of recycle. In general, however, both from the standpoint of yield and raw material cost, ethane is the best feed stock, but its use in externally heated reactors requires an ethane feed relatively free of methane and operation at high recycle ratio in a furnace of the best alloy steels operating near the limit of their strength; so that both capital and maintenance costs for the operation are high. Consequently, at the present time the greater part of the ethylene production of this country derives from the cracking of propane and heavier stocks.

By employing autothermic rather than tubular cracking it becomes practical to reach higher temperatures whereby the ethane in stabilizer gases containing 50% of methane can be cracked to the extent of 90% in a single pass.

Ethylene production by autothermic cracking from propane, from ethane, and from mixed stabilizer gases containing these hydrocarbons has been systematically studied; heavier feed stocks have also been examined.

Fundamentals

Thermochemical Efficiency. The ideal process illustrated in Figure 1 is schematically one in which hydrocarbon and air (or oxygen) pass through heat exchangers preheated by product gas, reach reaction temperature, are mixed, allowed to react, leave the reactor at their entering temperature, and then pass back through the heat exchangers; the

whole system being insulated to prevent any heat loss.

In such an ideal system the heat evolved by the exothermic reactions of combustion will just equal the heat absorbed by the endothermic reactions of cracking.

Thus the thermochemical efficiency of the process can be defined as 100% in the ideal case of over-all thermally balanced reactions; and in any actual practical operation:

thermochemical efficiency =

heat absorbed by cracking reactions
—————————————————————————
heat evolved by combustion reactions

However for rigorous quantitative use this definition requires that the temperature at which these heats of reaction are calculated should be defined, since their ratio varies slightly with temperature. Thus considering the ideal case defined now as one in which the feed gases are preheated to the identical temperature $T°$ of the gases leaving the reactor, in which a thermally balanced reaction takes place under adiabatic conditions at constant pressure, the total heat content of the product gases at $T°$ will be slightly greater than that of the entering gases. Since that increment of heat in the product gases can never be recovered even by ideally perfect exchangers, it is necessary to define the limiting ideal case by the ratio of the heats of cracking and combustion at $T°$, not the ratio computed from heats of reaction at the temperature of the cold end of the exchangers.

In the practical case besides a heat loss by radiation and convection to the outside, which is minor in large equipment, there is inevitably a substantial temperature difference across heat exchangers of economic design, thus the product gas leaves at a higher temperature than the entering feed streams. The consequent enthalpy loss in the warmer product gas and the minor heat loss by radiation are balanced by an additional consumption of air and combustion of hydrocarbon above the ideal minimum required for the given extent of cracking.

Thus looking at the process from the economic point of view, lowered thermochemical efficiency results in: (1) greater dilution of products with nitrogen; or if pure oxygen is used, increased amounts of oxygen consumed and (2) reduced ultimate yield of cracked products, because more of the feed hydrocarbon has been burnt as a fuel.

Thus the thermochemical efficiency defined in this way is a primary criterion by which to evaluate the merits of any such operation.

Reaction Temperature. It follows from the nature of the system that one

Fig. 1. Schematic flow diagram of autothermic process.

has not independent control of reaction temperature; any given ratio of feeds will on mixing rise to whatever temperature is necessary for the cracking reactions to catch up with and balance the heat evolution of the combustion reactions. Thereafter, the temperature will decline until endothermic cracking reactions have practically ceased owing to the decrease in temperature or to exhaustion of reactants; and in a given system of recuperative heat exchangers this final temperature will in turn determine the preheat temperature. Thus the whole temperature profile of the system will be adjusted downward by reducing the air-to-hydrocarbon ratio and so simultaneously the conversion; but for a given conversion the temperature profile in the reactor itself will not change appreciably by adding or removing heat-

exchange surface. If it is desired to change temperatures independently, it can however be done by injecting a third component, for example steam.

Typical temperature profiles when reacting propane and air are shown in Figure 2.

Chemistry. The molar ratio of oxygen to hydrocarbon required to produce substantial reaction covers the range from 0.1 to 0.5. The over-all reaction may therefore be considered as inverted combustion, that is the combustion of air in a large excess of fuel. Any reaction product can be schematically broken down into (a) cracked and unreacted products, whose over-all carbon-to-hydrogen ratio is that of the hydrocarbon feed, and (b) combustion products comprising carbon monoxide, carbon diox-
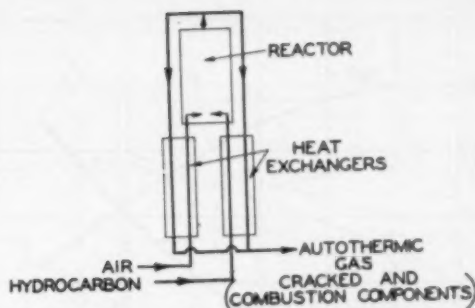
Fig. 2. Autothermic cracking of propane with air.
Temperature profiles in recuperative heat exchangers and reactor at 50% and at 95% propane conversion.
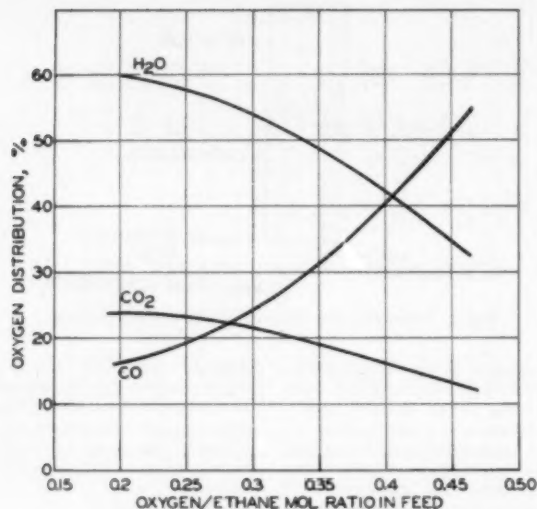
Fig. 3. Autothermic cracking of ethane.
Oxygen distribution among combustion components.

formation or catalyzes their reaction with hydrocarbon to carbon dioxide and hydrogen. These curves correlate all the data in several modifications and size of apparatus in which conditions have been such that no unreacted oxygen remains. Within the lesser accuracy of experiments using pure oxygen in place of air, results with oxygen fit the same correlation.

Figure 4 shows the same data as Figure 3 but with the ordinate scale expressed in terms of moles of combustion products. This shows that at the low ratios of oxygen to hydrocarbon the water formed is in excess of that corresponding to combustion of C_2H_6. This is noteworthy and from the point of view of ethylene production, favorable. It means that a substantial part of the ethylene has been formed from ethane without waste of feed hydrocarbon, by the ideal thermally balanced reaction.

$$C_2H_6 + 0.5 \ O_2 = C_2H_4 + H_2O$$
$$- 24.97 \text{ kg. cal. } (1200° \text{ K.})$$

$$0.724 \ C_2H_6 = 0.724 \ C_2H_4 + 0.724 H_2$$
$$+ 24.97 \text{ kg. cal. } (1200° \text{ K.})$$
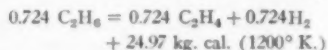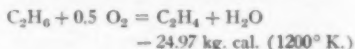
That is, the ideal yield theoretically attainable would be 3.448 moles of ethylene per mole of oxygen.

The oxygen distribution from propane is not quite as favorable.

Operating Conditions

Temperature. In accordance with the foregoing picture of the fundamentals, the process temperature does not enter in as a controlled variable. If the mean preheat temperature of the mixed gases falls below about 1050° F. the reaction will not start. This sets a minimum.

ide, water, and any excess (or deficiency) of hydrogen required to make the carbon-to-hydrogen ratio of this group also equal to that in the feed. There are also small amounts of aldehydes and organic acids, but these may be for the moment ignored. When such a breakdown is made it is found that the cracked products do not differ materially in distribution from what might be expected from externally heated thermal cracking under the same conditions of partial pressure, temperature, and residence time, if such conditions were practically obtainable; the combustion

products, however, show interesting and somewhat unexpected trends.

Figures 3 and 4 illustrate the relative quantities of these combustion products plotted against the oxygen-to-hydrocarbon ratio of the feed. These relate to experiments with ethane and air. Data from propane and air show a similar trend as indicated in Figures 5 and 6. Up to pressures of 30 lb./sq.in. gage there is no measurable change, but the ratios are markedly altered in the direction to be expected by the presence of iron or nickel in the reaction zone, which suppresses water and carbon dioxide

Fig. 4. Autothermic cracking of ethane.
Moles of various combustion components formed per mole of ethane burned.

Fig. 5. Autothermic cracking of propane.
Oxygen distribution among combustion components.

Fig. 6. Autothermic cracking of propane.
Moles of various combustion components formed
per mole of ethane burned.
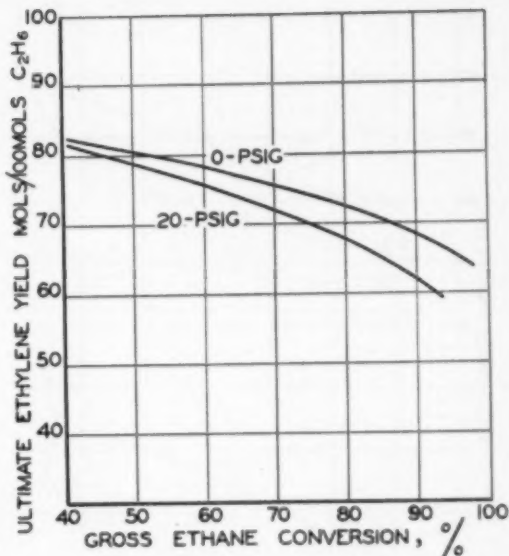
Fig. 7. Autothermic cracking of ethane.
Effect of reactor pressure on ultimate ethylene yields
at 80% thermochemical efficiency—
Ultimate yields on basis of ethane disappearance.

Within the range of experiments this practical threshold temperature is independent of mixture composition, and would seem to be that at which the combustion reactions proceed sufficiently fast to be effectively self-accelerating, and so to raise the whole mixture into the cracking region of temperature. In practice for stable operation a reactor profile which averages about 200° F. above this is the lowest encountered; and this corresponds to less than 30% conversion and is therefore of slight in-terest. As air-to-hydrocarbon ratio is increased the temperature profile rises as illustrated in Figure 2.

Pressure. The influence of pressure on the reaction is specific but not in any way critical, so that the choice is purely economic. With ethane there is more methane relative to ethylene in the product made at higher pressure and with propane more ethane relative to ethylene. Changes in other components are minor. Both these may be explained in the same way. The product gases are close to the ethane-ethylene-hydrogen equilibrium for the temperature-pressure conditions prevailing at the reactor exit. Pressure shifts this in the direction of ethane, while having no influence on the rate of methane formation. With ethane the magnitude of the effect reduces ethylene yield at 70% conversion about 5% on going from 1 to 3 atm. The change from the German condition of half an atmosphere to 1 atm. is less than analytical error. Pressures above 3
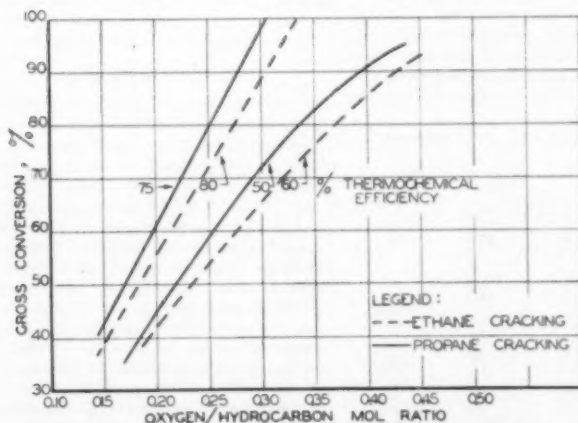
Fig. 8. Trend of conversion with oxygen to hydrocarbon.
Ratio in feed at various thermochemical efficiencies. Gross conversion
means % ethane or propane disappearing.
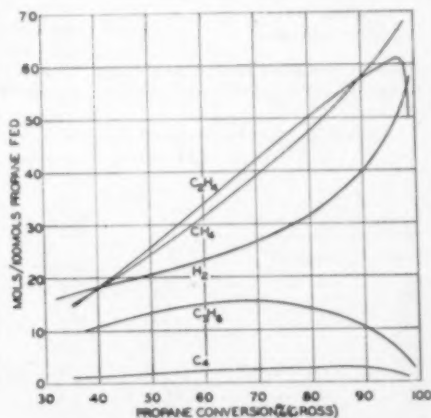
Fig. 9. Autothermic cracking of propane.
Products produced at about 50% thermochemical
efficiency (continued in Fig. 10).
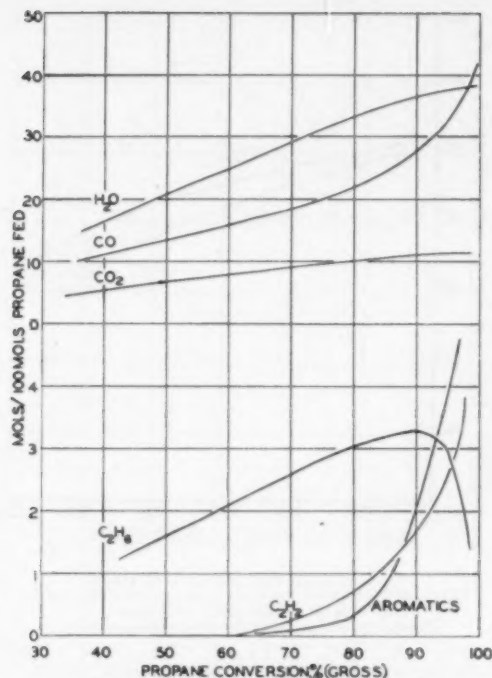
Fig. 10. Autothermic cracking of propane.
Products produced at about 50% thermochemical efficiency (see also Fig. 9).
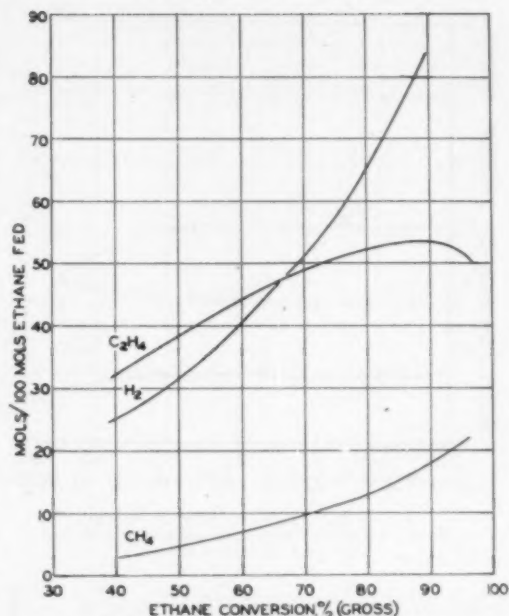
Fig. 11. Autothermic cracking of ethane.
Products produced at about 60% thermochemical efficiency (continued in Fig. 12).

atm. extend these trends and are of doubtful practical interest. The trend of this pressure effect with ethane is illustrated in Figure 7.

Throughput. At the temperatures reached, the reactions are fast and substantially complete in a few hundredths of a second residence time. Thus the reactor itself is small and compact. Up to fivefold longer residence makes negligible difference.

Air-to-Hydrocarbon Ratio. Other things being equal this primary variable con-trols temperature, conversion, and product distribution. Figure 8 illustrates the typical range of values.

Thermochemical Efficiency. The excess enthalpy of the cooled product gas over the feed streams corresponding to the temperature difference at the cold end of the exchangers can in practice be reduced to less than 20% of the heat generated by the combustion reactions. Radiation and convection losses on the pilot plant scale have also been about 20%, varying however with throughput; on the full scale these can be expected

to be less than 3%. Thus full-scale design of close to 80% thermochemical efficiency is entirely practical. In any given plant the thermochemical efficiency is likely to be changed little by other operating conditions since the contributing factors oppose one another. In particular the somewhat less complete heat exchange at higher throughput is offset by the reduction in radiation losses when expressed as percentage of the heat of combustion generated.

Product Distribution

Main Components. Variation of product gas composition with feed ratio for the autothermic cracking of propane and air and for ethane and air at 1 atm. is shown in Figures 9-12. These curves are drawn through the experimental points for a large number of runs in a pilot plant reactor having a thermochemical efficiency varying with conditions between 50 and 60%. Composition of the cracked portion of the gases is not changed if the thermochemical efficiency is varied by increase of heat-exchange surface or better insulation of the system. The quantity of combustion gases is reduced proportionately by raising thermochemical efficiency, and their composition is changed slightly in the direction of decreased

TABLE 1.—REPRESENTATIVE ANALYSES OF AUTOTHERMIC PRODUCT GAS

0 lb./sq.in. gage reactor pressure

Feed	Ethane		Propane		37/63 Methane/Ethane
Thermochemical efficiency	80	80	75	75	60
Conversion [1]	52.6	81.9	48.1	79.5	78
Product Gas Analysis [2]					
H₂	15.8	19.8	8.8	9.6	18.3
CH₄	2.7	5.9	11.6	17.3	19.0
C₂H₄	0.05	0.2	0	0.3	trace
C₂H₄	19.6	21.3	12.5	16.0	16.7
C₂H₆	22.1	6.6	0.8	1.1	5.3
C₃H₆	0.7	0.6	6.6	5.1	0.3
C₃H₈			24.3	7.2	0.1
C₄	.05	0.4	0.8	1.1	0.2
C₅	0	0	0	0.10	0
CO	2.1	4.5	4.2	4.9	5.5
CO₂	3.8	2.3	2.1	2.5	2.1
N₂	34.1	38.3	28.3	32.8	32.5
	100.0	100.0	100.0	100.0	100.0

[1] (100—% unreacted C₂H₆ or C₃H₈).
[2] Excluding H₂O.

amounts of hydrogen. Table 1 shows representative gas analyses of product gases.

Trace Components. The crude product gas contained minor amounts of formaldehyde and acetaldehyde and lesser amounts of organic acids. The total of these compounds does not amount to more than 0.1-0.2% of the hydrocarbon feed (carbon basis), so that they constitute a minor nuisance rather than a by-product.

It is noticeable that:

1. Aldehydes increase with decreased conversion of hydrocarbon, or decreased reaction temperature.
2. Acids are about 1/7 of the molar quantity of the aldehydes.
3. There is no pronounced effect of pressure on their yield.
4. With ethane about half the aldehydes is formaldehyde.

The formaldehyde and the acids condense out almost completely with the water of reaction forming a condensate containing 0.5-1.5% aldehydes which is about 0.5 N acidic. A little soda solution injection at this point neutralizes the acidity. The remaining aldehydes, nearly all acetaldehyde about 600 p.p.m. in the cooled gas, can be removed almost completely by water-scrubbing after compression.

Acetylene. Acetylene is negligible at hydrocarbon conversion levels below 50%/pass. At higher conversions it increases from around 1% of the ethylene at 75% conversion to 4-6% at 95% conversion depending on the feed. It can be converted to ethylene by passing the product gas over a selective hydrogenating catalyst. This purification step also converts butadiene to butylenes. There is no appreciable loss of ethylene.

Ethylene Yield. Ethylene yields can be summarized in several ways: (1) on the basis of gross hydrocarbon conversion, cracked plus burnt, (2) on the basis of moles per mole of oxygen used, and (3) on the basis of hydrocarbon cracked after deduction of that consumed by combustion reactions.

And for each of these bases different assumptions can be made as to losses in the recovery and recycling system and nature of components recycled, as well as in regard to thermochemical efficiency and pressure of the plant. To illustrate trends the curves of Figures 13, 14, and 15 show the ultimate ethylene yields, assuming no loss in the recovery and purification system, all acetylene being converted to ethylene, but only the components stated being recycled.

Figure 13 contains four different yield curves from ethane cracking. Curve *B* shows ultimate ethylene yields obtained in the pilot plant operating at about 60% thermochemical efficiency. Curve *A*
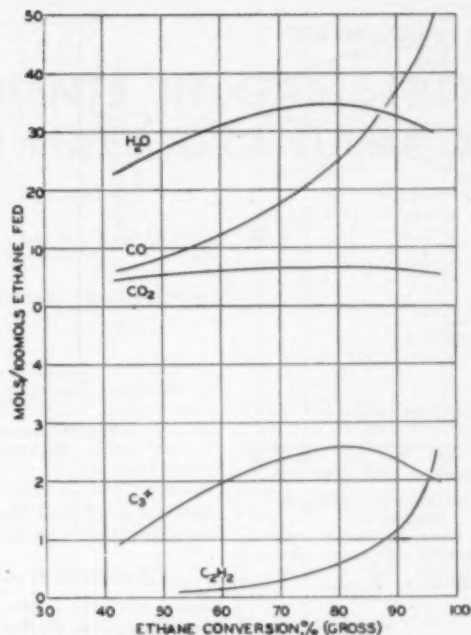
Fig. 12. Autothermic cracking of ethane.
Products produced at about 60% thermochemical efficiency
(see also Fig. 11).

shows ultimate yields on the cracked portion only—subtracting the burned portion of the ethane. This curve is added as a matter of interest to show how much yield is lost due to burning part of the feed. All other yield curves in this article are on the basis of cracked plus burnt. Curve *C* shows calculated yields anticipated in a commercial plant operating at 80% thermochemical effi-
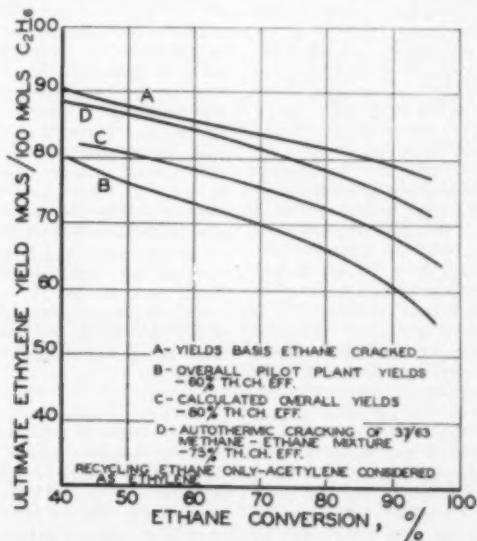
Fig. 13. Autothermic cracking of ethane at atmospheric pressure.
Ultimate ethylene yields.
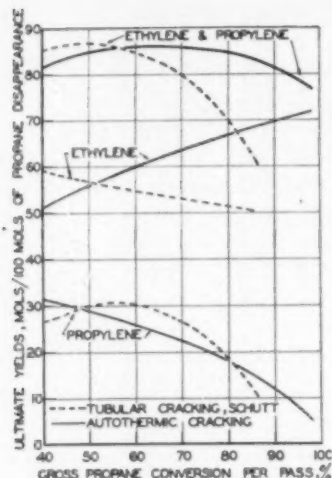
Fig. 14. Autothermic cracking of propane.

Ultimate olefin yields at 75% thermochemical efficiency. Recycling propane only—acetylene considered as ethylene.

Fig. 15. Autothermic cracking of ethane and of propane. Olefins yields on basis of oxygen consumed.

ciency. The increased yield shown by curve C over curve B indicates the improvement effected by increasing the thermochemical efficiency from 60% to 80%. Curve D shows that further improvement in ethylene yield can be obtained by using a dilute ethane feed containing 37% methane. This substantial gain in yield is due, primarily, to the methane supplying some of the heat by combustion. Thus, provided the product gas compressors and recovery system are sized appropriately, it is advantageous to feed stabilizer overhead gas containing 20 to 40% of methane, rather than feeding to the autothermic reactor exclusively pure ethane or the bottoms of the ethylene separation column.

Figure 14 compares autothermic yields of ethylene and propylene from propane with thermal yields reported by Schutt (2). The higher ethylene yields obtained in autothermic cracking at propane conversions above 50% are due primarily to the lower production of ethane by the autothermic technique. The higher ethylene and lower propylene yields are the result of the different pressure-temperature conditions and the time-temperature relationship effected by them. But the effect of propylene and ethane recycle in either case can alter product distribution so that this set of curves does not constitute a complete comparison of the two processes. It is noteworthy, however, that both ethylene and total olefin yields of the autothermic process exceed those reported for tubular cracking at higher

conversion levels where plant costs are lower due to smaller amount of recycle.

Full-Scale Process

Ethylene Recovery System. The autothermic process for ethylene is adaptable to more than one type of recovery system. Plants have been designed using a hypersorber to separate a C_2 fraction, followed by a moderately low temperature column at 250 lb./sq.in. gage to separate the ethylene from recycle ethane. Another has been planned to operate in conjunction with a conventional oil-absorption system.

Air or Oxygen. Experiments with oxygen have shown that the general behavior and yields are not materially different from those with air. Virtually the same product gas analyses omitting the nitrogen prevail. Therefore justification for the use of oxygen in place of air rests almost entirely on any saving it effects in the recovery system. It may be seen from the analyses that it raises ethylene concentration by about a third, eliminating about 30% of nitrogen from the product gas. On a large plant it is near an even break whether oxygen should be used. But its economic use recedes as thermochemical efficiency is raised. So far we have moved away from rather than towards the use of oxygen.

Conversion Level. It will be evident from the trends of product distribution and yield, that the choice of design conditions must be made in relation to each situation, and its available feeds and requirements. On the other hand, any given plant can be operated efficiently over a wide range of feed stock, conversion and throughput within the in-

stalled compressor capacity for air and product gas. The most concise summary therefore of the trends of plant capacity with operating conditions is implicit in the data of Figure 15 showing yields of olefin per unit of oxygen.
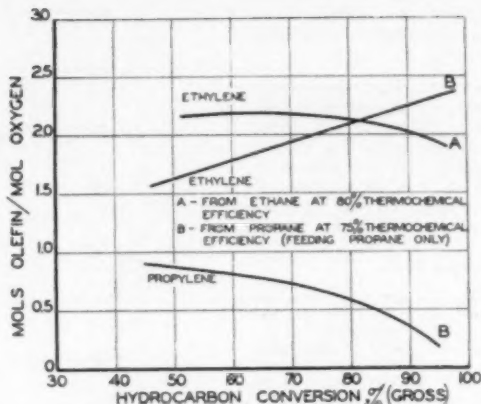
Conclusion

Apart from the simplicity and flexibility of the autothermic process in general it reveals certain inherent advantages over tubular cracking:

1. High ethane conversions (up to 96% per pass) are obtainable, in contrast to practical limitations of 50 to 60% in tubular reactors.
2. Dilute feeds containing as little as 50% of ethane may be cracked satisfactorily.
3. When cracking propane, butane, or heavier stocks, the C_2 cut contains 92 to 94% ethylene compared with 75 to 80% when using tubular furnaces.

Acknowledgment

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(Presented at Houston (Tex.) Meeting.)

TEMPERATURE GRADIENTS IN GAS STREAMS FLOWING THROUGH FIXED GRANULAR BEDS

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An experimental investigation was made of temperature gradients in air streams being heated while flowing through a cylinder packed with granular solids. From the measured temperature gradients, point values of the so-called effective thermal conductivity, k_e, were determined at various bed depths and radial positions for a range of mass velocities from 175 to 1215 lb./(hr.)(sq.ft.) and for three different particle sizes. Results indicate that in the range of variables studied k_e is a linear function of the mass velocity and the particle size of the packing. A correlation was obtained for k_e as follows:

$$k_e = 0.18 + 0.00098 G \sqrt{a_p}/\mu_m \qquad (1)$$

where

k_e = effective thermal conductivity under flow conditions, B.t.u./(hr.)(sq.ft.)(°F./ft.).
G = mass velocity based on the open tube, lb./(hr.)(sq.ft.).
a_p = surface area of particle of packing, sq. ft.
μ_m = arithmetic average of inlet and outlet gas viscosities, lb./(hr.)(ft.).

Experimental data showed that the resistance to heat transfer in the gas film at the inside of the tube wall is not negligible. A mathematical analysis of the longitudinal temperature gradients enabled values of h_w, the film coefficient of the gas adjacent to the inside of the tube wall, to be determined from the relationship

$$h_w = \frac{k_e J_1(\lambda_1)}{R \, J_0(\lambda_1)} \qquad (2)$$

where

h_w = B.t.u./(hr.)(sq.ft.)(°F.)
R = tube radius, ft.
$J_1(\lambda_1)$ = Bessel function of first order.
$J_0(\lambda_1)$ = Bessel function of zero order.
λ_1 = first characteristic value determined from the slope of the axial gas temperature gradient in the packed tube.

A preliminary correlation was obtained for h_w as follows:

$$h_w = 2.95 G^{0.33} \qquad (3)$$

Measurements of the velocity distribution of air flowing through packed tubes appeared to justify the assumption that rod-like gas flow occurs.

THIS paper will report the results of an experimental investigation of the temperature gradients in gas streams flowing through granular beds. Results are expressed in terms of the effective thermal conductivity of a granular bed through which gas is flowing and are

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correlated as a function of packing size and air velocity. A method is also presented for estimating the heat-transfer coefficient of the gas film at the inside wall of a packed tube. Both these quantities were calculated from measurements of the radial and longitudinal temperature gradients occurring in a packed tube when it was operated as a heat exchanger.

The occurrence of temperature gradients in beds of fixed granular solids is a problem frequently encountered in chemical engineering operations. The magnitude of these gradients and the factors influencing them should be known for the rational design and operation of reactors and heat exchangers of this type. The temperature gradients that arise when heating or cooling occurs in fixed-bed catalytic reactors are of particular interest. In the operation of such reactors, it is desirable practice to control the temperature within narrow limits to improve the selectivity of the reaction. One important method of effecting this control is by lateral heat transfer through the catalyst bed to a suitable heat exchanger. Hougen and Watson (9) describe four different types of bed arrangement for temperature control by lateral heat transfer. It should be noted that the problem of radial temperature gradients in packed tubes is difficult only when such gradients are established by heating or cooling, and not for adiabatic or isothermal reactors.

The rate of lateral heat transfer depends upon two factors: (1) the so-called effective thermal conductivity of the system, and (2) the heat-transfer coefficient of the gas film at the inside wall of the heat exchanger. Values of the effective thermal conductivity and of the heat-transfer coefficient of the gas film at the inside wall of the tube are therefore of fundamental importance in calculating temperature gradients. Smith and co-workers (1, 8) have reported a correlation of effective thermal conductivities for small particles. Their measurements were made in a 2-in. tube packed with ⅛-in. × ⅛-in. cylindrical alumina pellets. Nothing has been reported on the magnitude of and the factors influencing the heat-transfer coefficient of the fluid film at the wall of the heat exchanger in contact with the granular solid.

Previous Work

Numerous investigations on the problem of heat transfer and turbulence in beds of solids have been reported. Damköhler (3-5) developed differential equations for the temperature gradients in fixed bed reactors, and presented analytical solutions to the problem of determining temperature gradients for certain restricted cases.

Wilhelm, Johnson, and Acton (19) presented an analytical method for calculating radial and axial temperature gradients in a fixed-bed catalytic reactor under limited simplifying assumptions. Grossman (7) developed a complicated graphical solution to the problem using equations of finite differences. Wilhelm, Johnson, Wynkoop, and Collier (20) devised an electrical network calculator for calculating temperature gradients.

Regardless of the method used in calculating temperature gradients in catalytic reactors and heat exchangers packed with granular solids, certain fundamental data are required. These data include:

1. Reaction rate data and thermodynamic properties of reacting system.
2. The coefficient of heat transfer between the catalyst particles and the gas stream.
3. Effective thermal conductivity of the gas-solid system.
4. The heat-transfer coefficient of the gas film at the reactor tube or heat-exchanger wall in contact with the granular solid.

The thermodynamic and kinetic data must be determined from experimental studies of the particular reacting system. The heat-transfer coefficient between the catalyst particles and the gas stream can be determined from the correlations of Gamson, Thodos, and Hougen, and Wilke and Hougen (6, 18).

The thermal conductivity of granular materials without air flow has been studied by many investigators. In a review article Waddems (17) described the work of early investigators. More recently Schumann and Voss (16) presented a correlation of the thermal conductivity in static granular systems, and Wilhelm, et al. (20) extended the correlation to account for radiation. All this work, however, concerned static systems in which no gas flow occurred, and hence the correlations are not applicable to fixed granular beds under flow conditions.

Data on the effective thermal conductivity, k_e, for systems of gases flowing through granular solids are meager. Hall and Smith (8) reported an isolated value of k_e for $\frac{1}{8}$-in. $\times$ $\frac{1}{8}$-in. cylindrical alumina catalyst pellets in a 2-in. tube with an air mass velocity of 350 lb./(hr.)(sq.ft.) of open tube cross section. Hougen and Piret (10) reported a correlation of an over-all k_e based on studies of heat transfer to a gas flowing through a fixed granular bed.

Bunnell et al (1) reported values of k_e determined from measured temperature gradients. Values of k_e were correlated as a function of mass velocity for a single particle size and a rather limited velocity range. They did not report values of a film coefficient at the wall.

Over-all heat-transfer coefficients for packed heat exchangers have been reported by Colburn (2) and more recently by Leva and co-workers (11, 12). These coefficients are over-all coefficients based on mixed-mean temperature differences in the heat exchanger and give no basis for estimating radial temperature gradients. In calculating the radial temperature gradients in reactors, it is necessary to know the effective thermal conductivity of the system as well as the film coefficient of heat transfer of the fluid film at the wall rather than equivalent over-all coefficients. No values of the actual heat-transfer coefficient of the gas film at the wall in packed tubes have been reported.

Theoretical Development

Differential equations formulating the temperature gradients in catalytic reactors of simple geometric shape have been developed by numerous authors (3, 7, 9, 20). For a cylindrical reactor the partial differential equation for the gas temperature at any radial and longitudinal position and for the case of no circumferential variation may be written as follows:

$$\left(\frac{\partial t}{\partial z}\right) =$$

$$\frac{k_e}{GC_p}\left[\frac{\partial^2 t}{\partial x^2} + \frac{1}{x}\frac{\partial t}{\partial x} + \frac{\partial^2 t}{\partial z^2}\right] + \frac{Q}{GC_p} \tag{1}$$

z = axial distance along the reactor
x = radial distance
t = gas temperature
Q = rate of heat release/unit volume of reactor
G = mass velocity of gas through reactor
C_p = specific heat of gas
k_e = effective thermal conductivity of gas-solid system under flow conditions

In most cases, the heat transferred axially by conduction is small compared to that carried by the mass flow of the gas. This permits Equation (1) to be simplified by neglecting $(\partial^2 t/\partial z^2)$. Where no heat is released or absorbed by reaction or otherwise, i.e., the case

of a packed heat exchanger, the heat release term Q, becomes zero. Under these restrictions Equation (1) can be solved for k_e to give

$$k_e = \frac{GC_p\dfrac{\partial t}{\partial z}}{\left[\dfrac{\partial^2 t}{\partial x^2} + \dfrac{1}{x}\left(\dfrac{\partial t}{\partial x}\right)\right]} \tag{2}$$

Equation (2) was used to calculate values of k_e from experimentally determined temperature gradients.

Equation (2) can be integrated under suitable boundary conditions to give an equation expressing the temperature in the granular bed as a function of axial and radial position. One set of boundary conditions for the solution of Equation (2) can be expressed mathematically as follows:

At the entrance to the bed:
1. At $z = 0$, $t = t_o$ for all values of x. This assumes a uniform inlet temperature.

At axis of cylinder:
2. At $x = 0$, $(\partial t/\partial x) = 0$ for all values of z.

At inside surface of the cylinder:

3. At $x = R$, $-k_e\left(\dfrac{\partial t}{\partial x}\right)_R$
$$= h_w(t_w - t_R)$$

where:

R = inside radius of cylinder or tube
t_w = temperature of cylinder wall
t_R = gas temperature at $x = R$
h_w = film heat-transfer coefficient at inside surface of cylinder, adjacent to packing
k_e = effective thermal conductivity under flow conditions
t_o = uniform entrance temperature of gas

Equation (2) can be integrated for the above boundary conditions by methods outlined by Marshall and Pigford (14) to give Equation (3). (It should be noted that the integration of Eq. (2) assumes that G, mass velocity, is uniform across the tube; i.e., rod-like flow occurs.)

$$\frac{t_w - t}{t_w - t_o} = 2\sum_{n=1}^{\infty}\frac{J_o(\lambda_n\xi)e^{-\beta\lambda_n^2 z}}{\lambda_n[(\lambda_n m)^2 + 1]J_1(\lambda_n)} \tag{3}$$

where

$$\xi = x/R$$
$$\beta = \frac{k_e}{GC_pR^2}$$
$$m = \frac{k_e}{h_wR}$$

J_0 = Bessel function of zero order and first kind

J_1 = Bessel function of first order and first kind

The terms λ_n are usually designated as characteristic numbers or eigen-values and for the above boundary conditions are defined by the relationship

$$\frac{J_0(\lambda_n)}{J_1(\lambda_n)} = \lambda_n m \qquad (4)$$

Values of λ_n can be determined by a trial-and-error solution of Equation (4) or from the intersections on a plot of $\lambda_n m = y$, and $J_0(\lambda_n)/J_1(\lambda_n) = y$, as shown in Figure 1.

For values of βz greater than 0.2, the series in Equation (3) converges so rapidly that only the first term of the series is significant. Using only the first term of the series in Equation (3) and taking logarithms of both sides of the equation results in Equation (5).

$$ln\,\frac{t_w - t}{t_w - t_o} =$$
$$-\beta\lambda_1{}^2 z + ln\,\frac{J_0(\lambda_1 \xi)}{[\lambda_1[(\lambda_1 m)^2 + 1]J_1(\lambda_1)]} \qquad (5)$$

Thus when only the first term of Equation (3) is significant, Equation (5) predicts that a plot of the logarithm of the temperature ratio against bed depth will give a straight line of slope $-\beta\lambda_1{}^2$. Consequently if the experimental temperature gradients should plot as straight lines according to Equation (5) at sufficiently large values of z, then values of h_w can be calculated from the slopes of these lines. Thus, since the slope is $-\beta\lambda_1{}^2$, and β can be calculated from the relation $\beta = k_c/GC_p R^2$, λ_1 can be found. Substitution of this value of λ_1 in Equation (4) permits a determination of m, whereby h_w can be calculated. Thus, the working equation for calculating h_w may be written as

$$h_w = \frac{k_c \lambda_1 J_1(\lambda_1)}{R J_0(\lambda_1)} \qquad (6)$$

wherein λ_1 is determined from the slope of the curves

$$\log \frac{t_w - t}{t_w - t_o} \text{ vs. } z$$

Figure 7 is evidence that the experimental data are plotted in accordance with Equation (5).

Experimental Equipment and Procedure. It was decided that the most convenient way to determine point values of k_c would be to measure the radial and longitudinal temperature gradients in air flowing through a packed bed operated as a steady-state
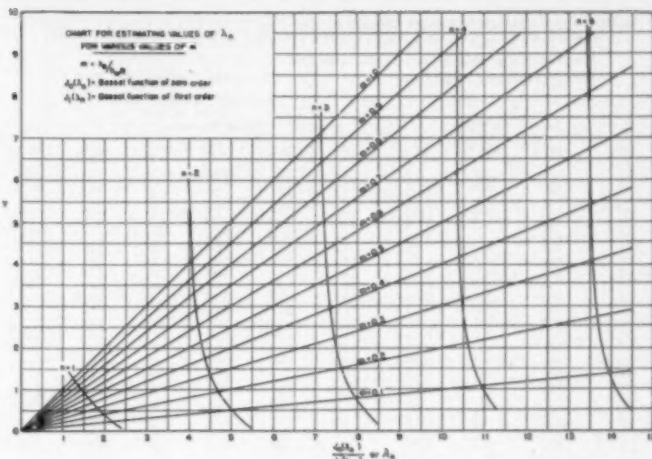
Fig. 1.

heat exchanger. A packed heat-exchanger type of apparatus was constructed for this purpose. Figure 2 shows a diagrammatic sketch of the experimental equipment.

The main apparatus consisted of a steam-jacketed, 5-in. pipe held vertically on a framework. The pipe was provided with a removable packing support at the bottom. A centrifugal-type blower together with the appropriate piping was used to force air upward through the bed. A gas-metering arrangement and cooling coils for controlling the inlet air temperature were installed between the blower and the entrance to the packed tube.

The jacketed pipe was constructed from standard pipe. The flanges at the ends were so constructed that the inner pipe

could be removed to permit use of a pipe of smaller diameter. (Only one diameter was studied in this investigation.) A pressure tap was provided at the bottom of the cylinder so that the pressure drop through the granular bed could be measured. Steam connections were attached to the jacket surrounding the packed tube.

At the bottom of the 5-in. pipe a packing support was fastened. This support was made of 10-mesh wire gauze placed on a supporting framework of 16 gage sheet metal. The strips of sheet metal in the framework were placed on edge so that they afforded little resistance to the flow of gas and yet provided a rigid support for the wire gauze. The packing support was removable so that the packing could be removed from the bottom of the tube.

The blower used to furnish air to the equipment was a Hoffman multistage
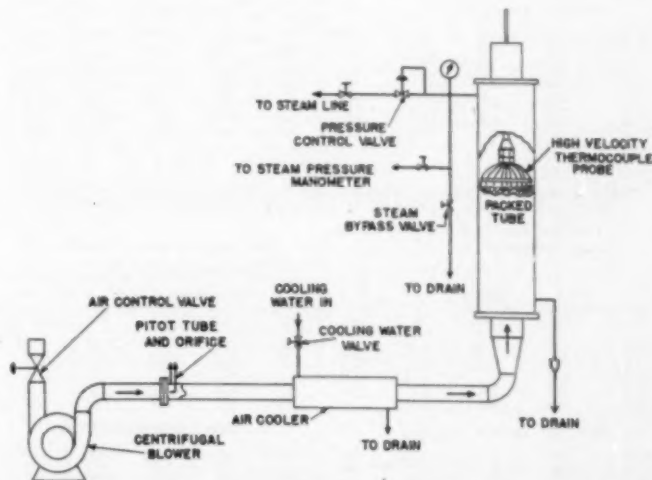
Fig. 2. Flow sheet of experimental equipment for determination of temperature gradients.

Packing: Celite 344, ⅜-in. × ½-in. cylinders.
Inlet Temperature: 100° F.   Tube Wall Temperature: 220° F.

Gas Temperatures, ° F.

Run No.	G, lb./(sq.ft.)(hr.)	Weight of Packing, lb.	z, in.	Radial Position, x, in.					
				0	0.5	1.0	1.5	2.0	2.44 in.
1-1	475	2.0	5.75	115	117	121	132	146	166
1-2	475	4.0	11.5	126	130	143	152	168	186
1-3	475	6.0	17.25	156	148	156	171	176	188
1-4	475	8.0	23.0	160	167	172	181	188	199
1-5	475	12.0	34.5	187	190	188	193	200	206
1-6	475	16.0	46.0	196	199	201	206	210	214
2-1	750	2.0	5.75	114	114	122	132	147	170
2-2	750	4.0	11.5	129	131	146	155	171	191
2-3	750	6.0	17.25	158	150	160	174	180	192
2-4	750	8.0	23.0	164	169	174	183	192	201
2-5	750	12.0	34.5	190	193	193	198	203	210
2-6	750	16.0	46.0	199	201	204	208	213	216
3-1	1005	2.0	5.75	115	115	123	134	147	171
3-2	1005	4.0	11.5	133	136	149	158	175	192
3-3	1005	6.0	17.25	163	154	164	177	184	195
3-4	1005	8.0	23.0	180	174	180	188	194	205
3-5	1005	12.0	34.5	194	197	197	202	207	214
3-6	1005	16.0	46.0	204	206	208	212	216	218
4-1	1215	2.0	5.75	119	120	130	140	156	183
4-2	1215	4.0	11.5	140	143	156	161	180	195
4-3	1215	6.0	17.25	170	163	172	188	191	202
4-4	1215	8.0	23.0	176	180	186	194	199	209
4-5	1215	12.0	34.5	201	204	204	208	211	216
4-6	1215	16.0	46.0	207	209	211	213	217	220

TABLE 2.—EXPERIMENTALLY DETERMINED GAS TEMPERATURES AT VARIOUS
RADIAL POSITIONS AND HEIGHTS IN A 5-IN. DIAMETER PACKED TUBE

Packing: Celite 410, ¼-in. × ¼-in. cylinders.
Inlet Temperature: 100° F.   Tube Wall Temperature: 220° F.

Gas Temperatures, ° F.

Run No.	G, lb./(sq.ft.)(hr.)	Weight of Packing, lb.	z, in.	Radial Position, x, in.					
				0	0.5	1.0	1.5	2.0	2.44 in.
5-1	475	2.0	4.5	113	114	119	137	150	184
5-2	475	4.0	9.0	123	128	136	155	173	198
5-3	475	6.0	13.5	130	137	143	165	182	207
5-4	475	8.0	18.0	144	146	154	169	183	198
5-5	475	12.0	27.0	165	171	179	191	200	209
6-1	750	2.0	4.5	111	112	114	124	143	173
6-2	750	4.0	9.0	116	118	127	146	167	193
6-3	750	6.0	13.5	122	128	136	159	177	200
6-4	750	8.0	18.0	134	137	145	162	180	200
6-5	750	12.0	27.0	160	168	177	189	200	211
7-1	1005	2.0	4.5	108	109	109	120	137	166
7-2	1005	4.0	9.0	111	114	121	136	158	186
7-3	1005	6.0	13.5	118	124	130	155	173	186
7-4	1005	8.0	18.0	126	131	139	158	175	196
7-5	1005	12.0	27.0	154	162	170	185	199	210
7-11	1215	2.0	4.5	108	108	109	120	135	166
7-21	1215	4.0	9.0	109	112	120	135	156	185
7-31	1215	6.0	13.0	116	121	129	149	170	197
7-41	1215	8.0	18.0	124	128	138	154	175	199

Runs 8-1 through 9-5   Inlet Temperature: 74° F.

8-1	175	2.0	4.5	104	112	118	134	160	198
8-2	175	4.0	9.0	133	140	153	167	187	209
8-3	175	6.0	13.5	157	164	172	187	202	218
8-4	175	8.0	18.0	181	182	187	196	208	219
9-1	310	2.0	4.5	92	96	101	122	150	192
9-2	310	4.0	9.0	106	112	131	149	173	202
9-3	310	6.0	13.5	127	142	149	168	186	210
9-4	310	8.0	18.0	150	152	162	174	195	214
9-5	310	12.0	27.0	177	179	184	194	207	211

TABLE 3.—EXPERIMENTALLY DETERMINED GAS TEMPERATURES AT VARIOUS
RADIAL POSITIONS AND HEIGHTS IN A 5-IN. DIAMETER PACKED TUBE

Packing: ⅜-in. × ⅜-in. Celite cylinders.
Inlet Temperature: 100° F.   Tube Wall Temperature: 220° F.

Gas Temperatures, ° F.

Run No.	G, lb./(sq.ft.)(hr.)	Weight of Packing, lb.	z, in.	Radial Position, x, in.					
				0	0.5	1.0	1.5	2.0	2.44 in.
10-1	475	2.0	4.25	106	108	109	118	142	193
10-2	475	4.0	8.5	110	113	117	135	170	203
10-3	475	5.0	10.75	114	116	127	147	179	208
11-1	750	2.0	4.25	105	103	108	116	141	182
11-2	750	4.0	8.5	105	105	110	124	156	196
11-3	750	5.0	10.75	109	110	117	137	171	202

Runs 12-1 through 13-3   Inlet Temperature: 74° F.

12-1	175	1.0	2.12	94	97	101	113	141	187
12-2	175	3.0	6.37	111	114	122	140	165	204
12-3	175	5.0	10.62	127	133	148	165	186	210
13-1	310	1.0	2.12	85	85	87	96	127	184
13-2	310	3.0	6.37	94	96	102	117	148	195
13-3	310	5.0	10.62	100	108	123	143	175	206

centrifugal-type capable of furnishing 150 cu.ft./min., at 3 lb./sq.in. p, measured under standard conditions, 32° F. and 1 atm. It was provided with a blast gate on the inlet for control of air flow.

The air from the blower passed through standard 2½-in. pipe to the air-metering equipment. The air-metering equipment consisted of a sharp-edged orifice with a Pitot tube in the center of the orifice. The static pressure tap for the Pitot tube was located at the downstream face of the orifice plate. The air velocity through the orifice was sufficiently high so that the velocity across the entire cross section of the orifice was uniform. This was verified by moving the Pitot tube to different points of the orifice cross section. The temperature at the orifice was measured by a high velocity thermocouple located just upstream from the orifice plate. Standard Pitot tube formulas were used to calculate the air rate through the equipment.

After leaving the metering equipment, the air passed over three cooling coils made of ¼-in. copper pipe. During tests of the equipment it was found that the blower required several hours to come to an equilibrium operating temperature. By circulating water through one or more of the cooling coils the air temperature at the entrance to the packed tube could be maintained constant even though the temperature of the air leaving the blower varied. By careful control of the flow rate of the cooling water, variations in the inlet air temperature were reduced to less than one degree.

The cooling section of the piping was connected to the packed heat exchanger by a removable section of sheet metal tube. A high velocity thermocouple was placed at the end of this section to measure the air temperature just before it entered the heat exchanger.

The steam pressure to the jacket of the tube was controlled by using a standard pressure-reducing valve. It was found that the steam demand of the equipment was so low that the pressure regulating valve did not work properly. This difficulty was overcome by installing a steam by-pass line so that steam could be drawn through the reducing valve continuously. The steam pressure was measured with a mercury manometer.

Temperature gradients in the bed were measured by high velocity thermocouples mounted on a special probe. Eleven copper-constantan thermocouples were mounted in 5/64-in. steel tubes supported on a metal cross bar. One tube was at the center of the bar while the others were equally spaced across the bar at intervals of ½ in. except for the two outermost tubes which were 7/16 in. from the next tubes. This made possible the measurement of temperatures 1/16 in. from the tube wall and at half-inch spacings across the tube diameter.

The small tubes were attached to a brass header. The header was threaded to a piece of ⅛-in. pipe about 8 ft. long. The thermocouple wires were led through the header, up the ⅛-in. pipe, and out through a gas-tight seal at the end of the pipe. A side outlet at the end of the ⅛-in. pipe was connected to a vacuum source.

The thermocouple wires were led to a multiple contact rotary switch so that the individual couples could be rapidly connected to a precision potentiometer.

Both wires of the couples were switched so that the danger of inaccurate readings due to short circuits between the couples was minimized. The switch used was a Mallory rotary switch with silver-plated

contacts. The cold junctions of the thermo-couples were placed in an ice and water bath.

The thermocouples were made of 26-gage copper and constantan wires. They were checked at room temperature periodically during the experimental runs to insure agreement.

The experimental procedure for measuring temperature gradients consisted of packing the tube to the desired depth, allowing the equipment to come to thermal equilibrium at a given air rate, and measuring the radial gas temperatures across four different sections of the tube spaced at 45° intervals. In packing the tube, the following procedure was used: The desired amount of packing material was weighed and dropped into the tube, a few particles at a time. Care was taken to obtain uniform packing of the tube. Almost no breakage of the particles occurred during this procedure. For the first temperature gradient measurements, 2 lb. of Celite 344, 3/8-in. × 1/2-in. cylinders were placed in the tube. The depth of the bed was carefully measured by lowering a measuring stick down the tube from above until it touched the packing. These observations revealed no marked irregularities in the surface of the packing. The thermocouple probe was lowered into the tube until the thermocouple tubes were nearly touching the packing.

After the tube had been packed, the steam to the jacket surrounding the packed tube was admitted and the blower started. The vacuum was adjusted to draw air through the high velocity thermocouples. The rate of air flow through the blower was adjusted to the desired value by the blast gate valve. The equipment was allowed to run for about 2 hrs. before any readings were taken. All parts of the equipment except the temperature of the air leaving the blower reached an equilibrium temperature rapidly. The temperature of the air leaving the blower increased slowly for several hours, and in order to compensate for this variation the air was cooled prior to the packed tube, as just described. The equipment was checked for equilibrium by taking temperature measurements in the packed tube until they showed no variation with time. The cooling water rate through the air cooler was controlled so that the air temperature at the inlet of the packed tube was 100° F., in most runs; 74° F. in the rest.

After the equipment had reached equilibrium, readings of impact head and static head at the orifice were taken. The gas temperature at the orifice was recorded. Barometric pressure, steam pressure, and pressure drop through the packed bed were recorded. Gas-temperature measurements were made with the high velocity thermocouples at four different sections in radial directions spaced at angles of 45°. This procedure was used in order to eliminate any irregularities in the temperature gradients due to local disturbances in the gas flow pattern.

The rate of air flow was then changed to another value, and the equipment again allowed to come to thermal equilibrium. Temperature measurements were taken as before. This procedure was repeated until data were obtained at all the desired air rates. The thermocouple probe was then removed and an additional amount of packing added to the tube. The procedure was repeated to give data for the new bed depth at the same air mass velocities used before.

For a given packed bed it was shown that the temperatures measured at the various points were reproducible. Thus, after a series of temperature measurements, the
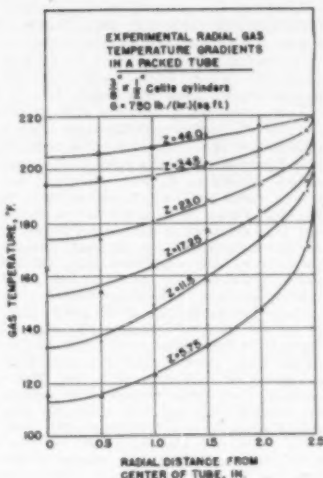
Fig. 3.

blower was turned off for a period of time, and then started again. After steady conditions had again obtained, temperatures were measured at various points and found to agree within 1° F. of the first values.

Data were taken for air mass velocities of 175, 310, 475, 750, 1005, 1215 lb./(hr.) (sq.ft.) for Johns Manville Celite cylindrical catalyst carrier in the following sizes: 3/8 in. × 1/2 in., 1/4 in. × 1/4 in., and 1/8 in. × 1/8 in. Above a mass velocity of 750 lb./(hr.) (sq.ft.), the 1/8-in. × 1/8-in. cylinders tended to fluidize, while the other sizes remained fixed for G in excess of 1215 lb./(hr.) (sq.ft.). Tables 1, 2, and 3 present tabulations of the measured radial temperatures for various depths of packing and for the three pellet sizes used. The temperature at each value of x represents an arithmetic average of eight circumferential readings space 45° apart.

In addition to the measurement of gas temperatures, isothermal air velocity measurements were made close to the top of the bed of packing. This was done to verify the assumption made in deriving Equation (1) and integrating Equation (2) that a gas flows through a packed bed in rod-like flow. Point velocities were measured with a hot wire anemometer. The anemometer was mounted on the end of a long rod provided with an adjustable spacing bar. The long rod was used to lower the anemometer close to the top of the packing in the tube and its radial position was adjusted by means of the spacing bar.

Measurements of air velocity were made as close to the surface of the packing as possible without breaking the anemometer wire, and at numerous positions on the tube diameter. Measurements were made with no packing, a thin bed of packing, and a thick bed of packing, and at high and low mass velocities. 3/8-in. × 1/2-in. cylinders and 1/4-in. × 1/4-in. cylinders were used in the velocity measurement runs.

Calculation Procedures

Calculations were divided into two parts. One part involved the determination of the equivalent thermal conductivity, and the other the calculation of

the film heat-transfer coefficient at the inside wall of the packed tube.

Determination of the Effective Thermal Conductivity, k_e: The gas-temperature gradients obtained by experimental measurement along four diameters of the tube were averaged arithmetically so that a single temperature gradient was obtained. The average temperature distributions taken at a single mass velocity and a particular particle size for different depths of bed were plotted as a function of radial position with bed depth as a parameter. A typical calculation procedure for the runs with Celite 344 (3/8-in. × 1/2-in. cylinders) at a mass velocity of 750 lb./(hr.) (sq.ft.) is outlined below.

Calculation of a Typical Run. The first step of the calculation procedure was to plot the measured gas temperature as a function of the radial position in the tube. Such a plot for a typical run is shown in Figure 3. In order to smooth the data and to obtain temperature gradients at more uniform increments of bed depth the data were cross-plotted as a function of bed depth as shown in Figure 4.

A smoothed plot of temperature as a function of radial position for various values of bed depth was then made as shown in Figure 5. This replotting of the data resulted in smooth plots that were self-consistent. It was shown that the smoothed plots of t vs. x represented the experimental data more precisely than the original plot of the data.

The smoothed plot of t vs. x was differentiated graphically to obtain $(\partial t/\partial x)_s$. The slopes were taken several times to ensure as accurate derivatives as possible. It was found that the derivatives could be reproduced quite well. The fact that a plot of $(\partial t/\partial x)_s$ as a function of x should be

Fig. 4.

Fig. 5.

Fig. 6.

$(\partial t/\partial z)_z$ at the positions in the granular bed at which $(\partial t/\partial x)_z$ and $\partial^2 t/\partial x^2$ had been taken. An examination of the values of $\partial t/\partial z$ showed that the value of $\partial^2 t/\partial z^2$ was small and hence justified neglecting this term in the derivation of Equation (2).

The corresponding values of $\partial t/\partial z$, $\partial t/\partial x$, and $\partial^2 t/\partial x^2$, together with the value of mass velocity and heat capacity were substituted into Equation (2), and a value of k_e determined. Values of k_e were calculated for several radial and longitudinal positions in the bed. Values of k_e at the various radial and axial positions in the bed are shown in Table 4 for a typical run. A single average value of k_e was established from all the point values for the particular air mass velocity and type of packing involved.

An arithmetic average of the point values of k_e was used in obtaining the reported value of average effective thermal conductivity. Since point values of k_e had been calculated at positions uniformly distributed across the tube diameter and through the depth of the bed this averaging procedure appeared as acceptable as any other. It is conceivable that k_e values for positions midway between the center of the tube and the wall might be more accurate and hence given more weight, but no justification on the basis of the data obtained could be given for such a procedure. Since the measured temperature gradients could be recalculated with good accuracy by using a value of k_e averaged in this way, this method of averaging was considered acceptable. It is true, however, that point values of k_e appeared to show a trend and the reason for this trend must be clarified by further investigation.

Regarding the method of calculating k_e, it is evident that the accuracy with which the various derivatives were obtained influences the accuracy of the values of k_e. In general, it is believed that the second derivatives are reliable within $\pm 20\%$. This is based on the reproducibility of the derivatives obtained by two individuals who checked one another on a set of second derivatives within $\pm 20\%$. Each individual started with only the experimental points and plotted the curves and performed the graphical differentiations independently.

smooth aided in differentiating the curves. The plot of $(\partial t/\partial x)_z$ vs. x is shown in Figure 6.

The line for $z = 5$ in. in Figure 6 might appear to be inconsistent with the other curves in the figure. However, this is not the case. The gas enters the bed with an essentially flat temperature profile. Near the entrance to the bed the gas temperature changes rapidly at the tube wall, but slowly near the center of the tube. Farther along in the bed, as the gas temperature becomes higher, the temperatures change more slowly and the gradients become less steep, as shown by experimental gradients.

The plot of $(\partial t/\partial x)_z$ vs. x was graphically differentiated to give $(\partial^2 t/\partial x^2)_z$. This derivative was taken at numerous points on the curves corresponding to the points at which values of $(\partial t/\partial x)_z$ were taken. The other derivative needed for substitution into Equation (2) to determine k_e was obtained from a plot of gas temperature as a function of bed depth for various radial positions. The plot of t vs. z (Fig. 4) was differentiated graphically to obtain

The contribution of the various derivatives to the value of k_e varied widely with both radial and longitudinal position. This variation may be seen from a tabulation in Table 3a of values of $1/x\,(\partial t/\partial x)$, and $(\partial^2 t/\partial x^2)$ for various positions in the bed.

Determination of Film Coefficient, h_w.—The calculation of h_w was made as follows: A plot of the unaccomplished temperature change, $(t_w - t)/(t_w - t_0)$, was plotted against bed depth, z, on semi-logarithmic paper. A plot for a typical run is shown in Figure 7. The slope of the straight portion of these curves was shown earlier to be equal to $-k_e\lambda_1^2/GC_pR^2$. Thus, from values of k_e determined above and the air mass velocity for a given run, λ_1 was determined. This value of λ_1 was then used in Equation (6) to calculate the value of the film heat-transfer coefficient at the wall. In the calculation of h_w, values of $J_0(\lambda_1)$ and $J_1(\lambda_1)$ were required. A plot of these functions up to the first two roots is shown in Figure 8.

Fig. 7.

Fig. 8.

5/8-in. × 1/2-in. Cylinders $\qquad$ G = 750

	5 in.		10		15		20		25		30		40	
z/z	$\frac{\partial^2 t}{\partial z^2}$	$\frac{1}{z}\frac{\partial t}{\partial z}$	$\frac{\partial^2 t}{\partial z^2}$	$\frac{1}{z}\frac{\partial t}{\partial z}$	$\frac{\partial^2 t}{\partial z^2}$	$\frac{1}{z}\frac{\partial t}{\partial z}$	$\frac{\partial^2 t}{\partial z^2}$	$\frac{1}{z}\frac{\partial t}{\partial z}$	$\frac{\partial^2 t}{\partial z^2}$	$\frac{1}{z}\frac{\partial t}{\partial z}$	$\frac{\partial^2 t}{\partial z^2}$	$\frac{1}{z}\frac{\partial t}{\partial z}$	$\frac{\partial^2 t}{\partial z^2}$	$\frac{1}{z}\frac{\partial t}{\partial z}$
0.0	14	14	22	22	21	22	17	17	12	12	10	10	9	8
0.5	14	14	21	21	17	22	13	16	7	10	7	8	6	8
1.0	15	15	18	21	13	18	8	14	6	11	5	7	4.5	6
1.5	18	14.7	12	18.7	10	15.3	7	11.3	7	8.7	6	6.7	4	4.7
2.0	26	17	13	17	10	14.5	8	10.5	8	9	7	9	6	5
2.4	29	19	18	16.7	9	13.3	9	10	10	9.3	9	3.7	10	5.4

TABLE 4.—VALUES OF k_e FOR VARIOUS POSITIONS IN A BED OF 5/8-IN. × 1/2-IN. CELITE CYLINDERS

G = 750 lb./(hr.)(sq.ft.) $\qquad$ $(k_e)_{avg} = 1.31$

z, in./z, in.	5	10	15	20	25	30	40
0.0	1.04	1.33	1.25	1.29	1.34	1.24	0.82
0.5	1.30	1.36	1.27	1.51	1.72	1.46	1.20
1.0	1.61	1.42	1.56	1.59	1.63	1.76	1.25
1.5	1.92	1.81	1.50	1.51	1.30	1.07	1.34
2.0	2.90	1.75	1.19	1.10	1.09	0.86	0.93
2.4	1.61	1.22	0.92	0.77	0.64	0.81	0.57

NOTE: In Equation (2), $\lim_{z\to 0}\frac{1}{z}\frac{\partial t}{\partial z} = \frac{\partial^2 t}{\partial z^2}$. Hence, at $z = 0$,

$$k_e = \tfrac{1}{2} G C_p (\partial t/\partial z)/(\partial^2 t/\partial z^2).$$

Results and Correlations. Values of effective thermal conductivity were obtained in a 5-in. tube for 1/8-in. × 1/8-in. Celite cylinders at mass velocities ranging from 175 to 750 lb./(hr.)(sq.ft.) above which fluidizing occurred; for 1/4-in. × 1/4-in. Celite cylinders at mass velocities from 175 to 1215 lb./(hr.) (sq.ft.), and for 5/8-in. × 1/2-in. Celite cylinders at mass velocities from 475 to 1215 lb./(hr.)(sq.ft.). Average values of k_e obtained are shown in Table 5. Data showed the effective thermal conductivity to be a function of the air mass velocity and the particle size of the packing. Various average values of k_e were plotted as a function of the modified Reynolds' number $G\sqrt{a_p/\mu_m}$. Although the viscosity of the gas was nearly constant for all the runs, it was included in the correlation because it was believed that the Reynolds' number should be the correlating group for the turbulent phenomenon associated with the effective thermal conductivity. Figure 9 shows a linear plot of k_e as a function of $G\sqrt{a_p/\mu_m}$. This correlation may be expressed by the empirical equation

$$k_e = 0.18 + 0.00098 \frac{G\sqrt{a_p}}{\mu_m}$$

(7)

where

k_e = effective thermal conductivity, B.t.u./(hr.) (sq.ft.) (° F./ft.)

G = mass velocity based on open cross section of tube, lb./(hr.)(sq.ft.)

a_p = external surface area of particle, sq.ft.

μ_m = arithmetic average gas viscosity, lb./(hr.)(ft.)

Also shown on Figure 9 are the data of Bunnell et al (1), which cover only a limited range but agree reasonably well with the correlation.

Values of the gas-film coefficient of heat transfer at the inside of the tube wall were calculated for 1/4-in. × 1/4-in. cylinders at mass velocities ranging from 175 to 1215 lb./(sq.ft.)(hr.) and for 5/8-in. × 1/2-in. cylinders for mass velocities from 475 to 1215 lb./(sq.ft.) (hr.). Values of h_w are listed in Table 6 and are shown plotted as a function of mass velocity in Figure 10. This correlation is expressed by the following equation:

$$h_w = 2.95 G^{0.33}$$

(8)

where

h_w = gas film heat-transfer coefficient at inside of tube wall, B.t.u./(hr.)(sq.ft.) (° F.)

G = mass velocity of gas based on open cross section of tube, lb./(sq.ft.)(hr.)

The isothermal velocity measurements showed that even for quite thin beds of packing the velocity profile of the gas is different from that for a gas flowing through an open tube, Figure 10a shows a typical velocity traverse taken near the exit of the packed bed. The point velocities are quite irregular due to jets of air issuing between the particles, but it is not an unexpected result. On the basis of curves of this type it was assumed that the gas velocity does not have any marked trend which might discredit unduly the assumption of rod-like flow made in the integration of Equation (2). This assumption seems further justified in view of the good check obtained when the observed temperature gradients were recalculated. (Fig. 13.) Velocity traverses for greater bed depths showed a similar irregular pattern.

TABLE 5.—SUMMARY OF AVERAGE VALUES OF k_e

G	175	310	475	750	1005	1215
1/8-in. × 1/8-in. cylinders	0.30	0.42	0.50	0.60	....	....
1/4-in. × 1/4-in. cylinders	0.32	0.38	0.57	0.90	1.28	1.27
5/8-in. × 1/2-in. cylinders	....	....	0.97	1.31	1.86	2.01

TABLE 6.—VALUES OF GAS FILM HEAT-TRANSFER COEFFICIENT, h_w

G	175	310	475	750	1005	1215
1/4-in. × 1/4-in. cylinders	22	15	12	31	46	18
5/8-in. × 1/2-in. cylinders	..	..	21	28	29	33

TABLE A

z, in.	$\xi = 0$		$\xi = 0.2$		$\xi = 0.4$		$\xi = 0.6$		$\xi = 0.8$		$\xi = 1$	
	Y	t	Y	t	Y	t	Y	t	Y	t	Y	t
17.25	0.580	150	0.557	153	0.501	160	0.414	170	0.293	185	0.163	200
25.0	0.372	175	0.380	177	0.322	181	0.267	188	0.185	198	0.102	208
46.0	0.113	206	0.108	207	0.0968	208	0.0780	211	0.0520	214	0.03	217

NOTE: $Y = \dfrac{t_w - t}{t_w - t_0}$

Fig. 9.

Fig. 10.

Discussion of Results

From the correlation of k_e as a function of the modified Reynold's numbers, $G\sqrt{a_p/\mu_m}$, (Fig. 9), it seems permissible to conclude that the effective thermal conductivity is a measure, primarily, of the lateral transport of heat due to turbulence in the packed bed. Thus, all the factors contributing to an increase in turbulence also contribute to an increase in k_e. It should be noted, however, that since only packings of low thermal conductivity were studied, no effect of this variable was observed. It is conceivable that a packing with a high thermal conductivity might contribute significantly to the lateral heat transfer in a packed bed.

The correlation obtained for k_e is interesting in the light of Equation (2) which states that k_e should be a function of G and the ratio of the longitudinal temperature gradients to the derivative of the radial temperature gradient. Since k_e is assumed constant for any position in the bed for given conditions of air flow and packing size, it might have been presupposed only as a special case that the ratio

$$\frac{\partial t}{\partial z} \Big/ \frac{1}{x}\frac{\partial}{\partial x}\left(\frac{x\partial t}{\partial x}\right)$$

would be constant for any set of conditions. However, the experimental results tend to show that since k_e is a linear function of the superficial mass velocity and a characteristic dimension of the packing, the ratio

$$\frac{\partial t}{\partial z} \Big/ \frac{1}{x}\frac{\partial}{\partial x}\left(\frac{x\partial t}{\partial x}\right)$$

is always constant and independent of G.

Viscosity of the air was included in the correlation for the sake of generality, although the total variation of this factor was not more than about 30 per cent. Therefore, the effect of viscosity requires further study, especially for the case of steep temperature gradients covering large radial temperature drops. The value of viscosity used in the correlation is an arithmetic average of the inlet and outlet viscosities.

The effect of natural convection on k_e was not investigated in this study, but it is anticipated that it might be significant at low mass velocities, and for packed tubes operating in a horizontal position.

It was interesting to note from velocity measurements that temperature and velocity gradients fail to show the correspondence that occurs in turbulent flow in empty tubes. In an early study, Pannell (15) made velocity and temperature explorations in a turbulent air stream being heated while flowing through a 1.92-in. diameter pipe. The correspondence between velocity and temperature is shown in Figure 67 of McAdams (13). In the study reported here, measurements of radial velocity distribution just above the packing were made with a hot wire anemometer. Results showed that the velocity gradients and temperature gradients in packed tubes do not show the correspondence found for these gradients for turbulent flow in open tubes.

Since the effective thermal conductivity presented in this study is derived from point values of temperature gradients, it differs from the over-all conductivity of Hougen and Piret (10) who combined the effect of the film coefficient with the effective conductivity. The only published values for k_e comparable to
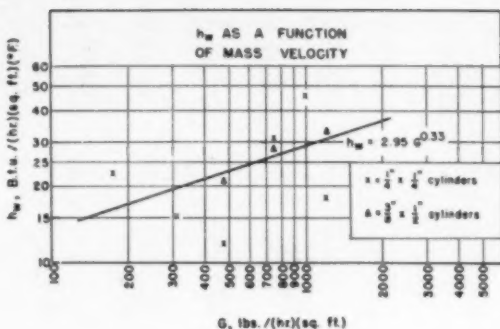
the k_e used in this paper are the values of Hall and Smith (8) and Bunnell, Irvin, Olson and Smith (1). These values were calculated from data taken in a 2-in. tube at relatively low Reynolds numbers. They are shown plotted in Figure 9 for comparison, and fall below the present correlation. A linear relationship between k_e and Reynolds number was presented by Bunnell et al (1), and may be written as $k_e = 0.125 + 0.0007G\sqrt{a_p/\mu_m}$ for comparison with Equation (7). In view of the differences between the systems and the experimental procedures, agreement between the two correlations appears to be satisfactory. It is of interest to note that Hall and Smith (8) also neglected the gas-film resistance and extrapolated their experimental temperature gradients to the wall temperature. This was initially done in the study reported here, but on attempting to reproduce the experimental temperature gradients, it was found that the film resistance at the inside of the tube wall, $1/h_w$, was appreciable and must be taken into account. When k_e and h_w were taken into account the experimental temperature gradients were reproduced quite well. The method of using k_e and h_w to reproduce the gradients for a typical run is illustrated by the following example:

Example:

Conditions:

Mass velocity = 750 lb./(hr.) (sq.ft.)
Packing = ⅜-in. × ½-in. Celite cylinders
Inlet temperature = 100° F.
Modified Reynolds number = $G\sqrt{a_p/\mu_m}$ = 1280
$\sqrt{a_p}$ = 0.0925 ft.
μ_m = 0.0484 lb./(hr.) (ft.)
R = 2.5 in. = 0.208 ft.

From Figures 9 and 10 values of k_e and h_w are 1.38 B.t.u./(hr.)(sq.ft.)(° F./ft.) and 26.5 B.t.u./(hr.)(sq.ft.)(° F.) respectively.

In order to calculate the gradients from the above data, it is necessary to have a set of curves similar to those in Figure 7 for the appropriate value of m, the ratio of (k_e/R) to h_w. If such a set of curves must cover a wide range of values of β_z, including values less than 0.2, then the curves must be calculated for the desired m values from the series given by Equation (3). However, temperature gradients may be estimated for values of $\beta z > 0.2$ without evaluating the series by means of the working chart shown in Figure 11. This chart is a plot of $(t_w - t)/(t_w - t_o)$ for various values of m at two values of β_z, and several values of ξ. To prepare a set of curves for estimating temperature gradients, it is necessary to determine only the required value of m, and from Figure 11 establish by a cross-plot two sets of points of $(t_w - t)/(t_w - t_o)$ and ξ, one set for $\beta z = 0.2$ and the other for $\beta z = 0.7$.

These sets are then plotted as $(t_w - t)/(t_w - t_o)$ vs. βz on semilog paper, and straight lines drawn between each pair of points corresponding to a given ξ. To illustrate this procedure for the calculation at hand, it was found that the value of m is:

$$m = k_e/h_w R = \frac{1.38}{26.5 \times 0.208} = 0.252$$
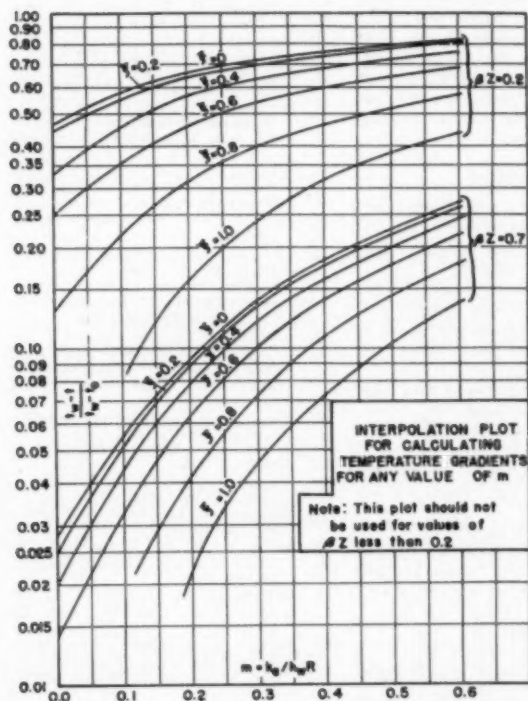
From Figure 11, two sets of points at $\beta z = 0.2$ and $\beta = 0.7$ are selected corresponding to a value of $m = 0.252$. These are plotted on semilogarithmic paper in Figure 12. Extrapolation of the curves on Figure 12 below $\beta z = 0.2$ is not valid.

Temperature gradients now can be determined from cross-plots on Figure 12 at various prescribed bed depths. For the conditions at hand, $\beta = k_e/GC_pR^o = 1.38/(750 \times 0.25 \times 0.208^o) = 0.170$. If temperature gradients are estimated at $z = 17.25$, 25.0 and 46.0 in. the corresponding values of βz are: 0.246, 0.354, and 0.652, respectively. The tabulation on p. 147 (Table A) gives the corresponding values of $(t_w - t)/(t_w - t_o)$ and t at various ξ's and at three bed depths.

The calculated values of t in Table A are plotted as a function of ξ in Figure 13 and compared with the experimentally determined values. It will be observed that the comparison is favorable. Also plotted on Figure 13, is a radial temperature gradient curve at $z = 17.25$ in. for the case of $m = 0$; i.e., no resistance at the wall. It is evident from this curve that the customary assumption of negligible resistance in the gas film at the inside of the tube wall is scarcely justified.

Errors in the inlet-gas temperature and the tube-wall temperature are of no consequence in the experimental evaluation of k_e, since the calculation of
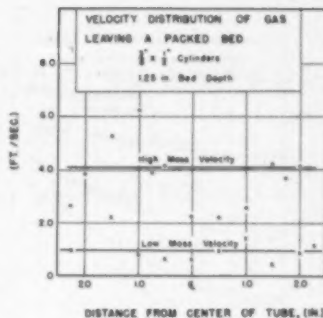
Fig. 10a.

k_e does not involve either temperature. However, the inlet and the tube-wall temperatures are used in calculating the value of h_w. Nevertheless, errors in these two measurements do not greatly affect the slope of the curves (Fig. 7) used to determine λ_1, and subsequently h_w. This was verified by a trial calculation using an inlet temperature of 104° instead of 100° F. All the curves in

Fig. 11.
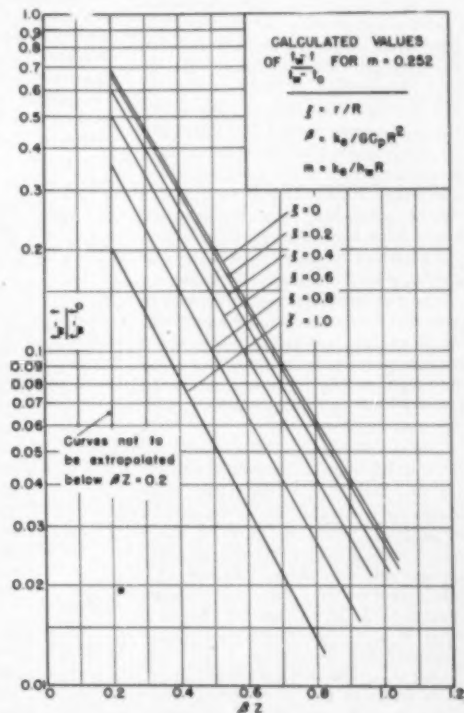
Fig. 12.
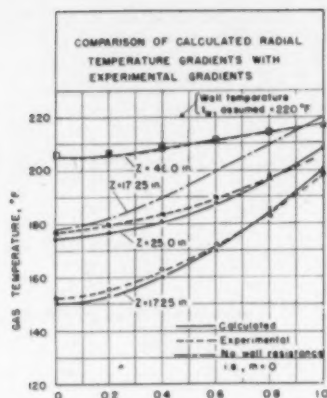
Fig. 13.

Figure 7 were merely moved upward by the increase in inlet temperature, but the slope of the curves was unchanged. This indicates that the value of h_w is relatively insensitive to the value of inlet-gas temperature. However, in recalculating the temperature gradients for Figure 13 with the values of k_e and h_w taken from the correlations it was noted that an error in the inlet temperature causes a significant error in the calculated temperature gradients. Thus when the gradients were calculated for an inlet temperature of 105° instead of 100° F., the values checked more nearly the experimental points. This might lead one to conclude that the value of inlet temperature used in the calculations was lower than actual. This is more than a remote possibility, since the inlet air might have been heated by the equipment between the point of measurement and the point of entrance to the tube.

The fact that h_w is significant can be explained on the basis that the tube wall forces the gas to lose the turbulence it attained in the packing and to flow along the wall thereby creating the usual laminar layer and the resistance to heat flow associated with it.

The correlation of h_w as a function of G (Fig. 10) shows a scattering of points for the $\frac{1}{4}$-in. $\times$ $\frac{1}{4}$-in. cylinders. This scattering is due, in part, to the method of analysis. The value of h_w is determined from a ratio of Bessel functions of zero and first order, Equation (6). The nature of these functions is shown in Figure 8. It is apparent that if a value of λ_1, as determined from Figure 7, approached a root of $J_o(x)$; i.e. $J_o(\lambda_1) \to 0$, then the calculation of h_w from Equation (6) is extremely sensitive to a small error in λ_1. The curved lines in Figure 1 also show how the ratio

of $J_o(x)/J_1(x)$ varies extremely rapidly as x approaches a root of $J_1(x)$. Consequently, values of h_w might be expected to involve rather large errors when calculated for values of λ_1 greater than 2.1, the first root of $J_o(x)$ being 2.4048. The value of λ_1 for $\frac{1}{4}$-in. $\times$ $\frac{1}{4}$-in. cylinders was in the vicinity of this first root.

The case where $\lambda_1 = 2.4048$, a root of $J_o(x)$, is the condition of zero resistance in the gas film at the wall. The fact that λ_1 appears to approach this value as the packing size decreases might mean that small particles tend to disrupt any laminar film which exists along the wall.

It is believed that further studies will show that h_w is a function of particle size, so that actually two lines might be drawn on Figure 10 for the two different sizes of particles involved.

Values of the over-all heat-transfer coefficient calculated for several runs from mixed mean gas temperature checked well with the correlated values of Leva and co-workers (11, 12).

Further work is required to establish the effect of viscosity and tube diameter on k_e, and the effect of particle size on h_w.

Acknowledgments

Notation

a_p = external surface area of a particle, sq.ft.

C_p = heat capacity of gas, B.t.u./(° F.)(lb.)

G = mass velocity based on open tube, lb./(hr.)(sq.ft.)

h_w = gas-film coefficient at inside of tube wall, B.t.u./(hr.)(sq.ft.)(° F.)

$J_o(x)$ = Bessel function of zero order and first kind

$J_1(x)$ = Bessel function of first order and first kind

k_e = effective thermal conductivity, B.t.u./(hr.)(sq.ft.)(° F./ft.)

m = resistance ratio = $k_e/h_w R$

n = index of summation, Eq. (3)

Q = rate of heat release per unit volume of reactor, B.t.u./(cu.ft.)(hr.)

R = tube radius, ft.

t = gas temperature, ° F.

t_a = uniform inlet gas temperature, ° F.

t_R = temperature of gas at gas film adjacent to tube wall, ° F.

t_w = temperature of tube wall, ° F.

x = radial distance from center of tube, ft. (Expressed as in. on the various figures)

$Y = (t_w - t)/(t_w - t_o)$

z = distance along tube axis, ft. (Expressed as in. on the various figures.)

GREEK:

$\beta = k_e/GC_pR^2$, 1/ft.

$\xi = x/R$, dimensionless

λ_n = characteristic values defined by Eq. (4), dimensionless

μ = viscosity of gas, lb./(ft.)(hr.)

μ_m = arithmetic average of inlet and outlet gas viscosities, lb./(ft.)(hr.)

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BOILING COEFFICIENTS OF HEAT TRANSFER

C_4 Hydrocarbon-Furfural Mixtures Inside Vertical Tubes

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ALTHOUGH several investigators have studied the evaporation of pure liquids in forced convection inside of vertical tubes (3, 15, 20), experimental data on boiling heat-transfer coefficients are not readily available for the case of liquid mixtures of widely different volatilities. Opportunity to measure such coefficients was afforded through study of the operating characteristics of a reboiler which was installed as part of a pilot plant distillation column specially designed to measure plate efficiencies in extractive distillation systems (12). The reboiler of this unit received from 12 to 43 gal./min. of a boiling liquid mixture of butylene, butane, and furfural containing from 0 to 15 mole % of the C_4 hydrocarbons. This liquid passed upward in forced convection through 163 ¾-in. tubes, 14 B.W.G., slightly more than 10 ft. long. Pressure of operation was from 0 to 60 lb./sq.in. gage. Because of the low volatility of the furfural (its normal boiling point is 323° F.), operation of the reboiler could easily be carried out so as to vaporize nearly all the C_4 hydrocarbons with negligible vaporization of the furfural. Under such conditions, the effect of percentage vaporization of the reboiler feed could be easily studied and controlled by variation of the C_4 hydrocarbon content of the reboiler feed.

Realizing that the reboiler itself was of sufficient size so that operating data would probably be applicable to commercial exchangers, and that as part of an experimental unit the reboiler could

be tested under widely varying yet carefully controlled conditions, an experimental program was undertaken. The purpose of the program was not only to measure heat-transfer coefficients for the process (tube) side of the reboiler, but to study the effect of mass velocity and fraction of the inlet feed vaporized upon the magnitude of the coefficients.

Boarts, Badger and Meisenburg (3) studied the change in temperature of water as it rose upward in the tube of a vertical forced-circulation evaporator. They found that as the fluid passed up the tube, the temperature increased until boiling started, then decreased through the boiling section as the hydrostatic head above the fluid decreased. McAdams, Woods, and Bryan (16) observed the same phenomena in a horizontal tube, although the decrease in temperature through the boiling section was caused only by the lowering of pressure due to pipe friction and was therefore smaller than the case where hydrostatic liquid head was present. McAdams, Woods, and Heroman (17) used the same horizontal tube apparatus to vaporize benzene-oil mixtures, which are similar to the mixtures employed in this study since the components were of widely varying volatility. These investigators found a steady increase in the temperature of the process fluid as it moved through the tube in contrast to the decrease in temperature found in the boiling zone when water was the fluid employed. The steady temperature increase obtained with benzene-oil mixtures was attributed to the fact that the decrease in boiling point of the liquid caused by the pressure drop through the tube was more than counterbalanced by the increase in boiling point resulting from removal of benzene from the liquid by vaporization.

In both the benzene-oil and water vaporization studies in the horizontal tube, McAdams, et al. (16, 17) meas-

ured the progressive change of heat-transfer coefficients along the tube. These coefficients first increased as the fluid mixture passed through the tube, then decreased rapidly after 50 to 70% of the feed had been vaporized. This latter behavior was attributed to insufficient liquid remaining to wet completely the walls of the tube for the case of water vaporization. However, for the vaporization of benzene-oil mixtures, it was shown that the decrease in coefficient at the higher vaporization resulted from depletion of benzene in the liquid phase causing a corresponding increase in liquid viscosity. Data from the benzene-oil studies (17) will be compared with the results of this paper in a later section.

The experimental program for the present study was somewhat limited by the amount of vapor which could be generated. This quantity was largely determined by the C_4 hydrocarbon content of the inlet feed to the reboiler, and at the highest pressure of operation employed (60 lb./sq.in. gage) did not exceed 15 mole % C_4 hydrocarbon. Under these conditions of low vaporization it was not expected that the local heat-transfer coefficient would diminish along the tube length due to vapor binding, or that the critical temperature difference would be exceeded.

The final experimental program consisted of four series of runs, each with a separate constant fractional vaporization of the process fluid entering the reboiler as follows: 0, 2, 5, and 10-12 mole % vaporized. Each series of runs was carried out over a range of mass velocity, G, from 20,000 to 80,000 lb./(hr.)(sq.ft.) of tube cross section, corresponding to flow rates of from 12 to 43 gal./min. Reynolds numbers inside the tubes were varied from 600 to 2700, when evaluated with G as the total mass flow rate, and μ as the viscosity of the liquid at its mean temperature.
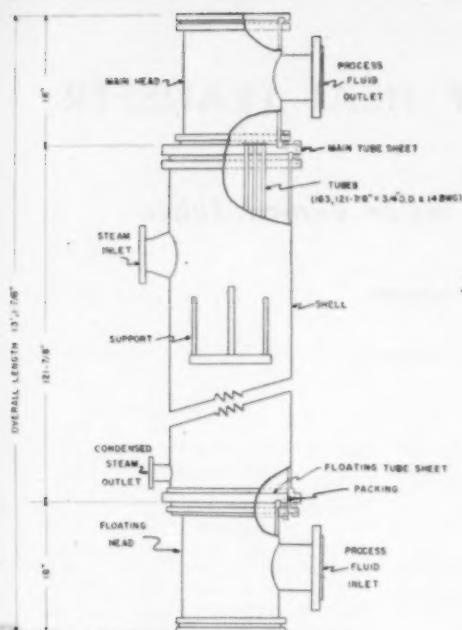
Fig. 1. Schematic view of reboiler.
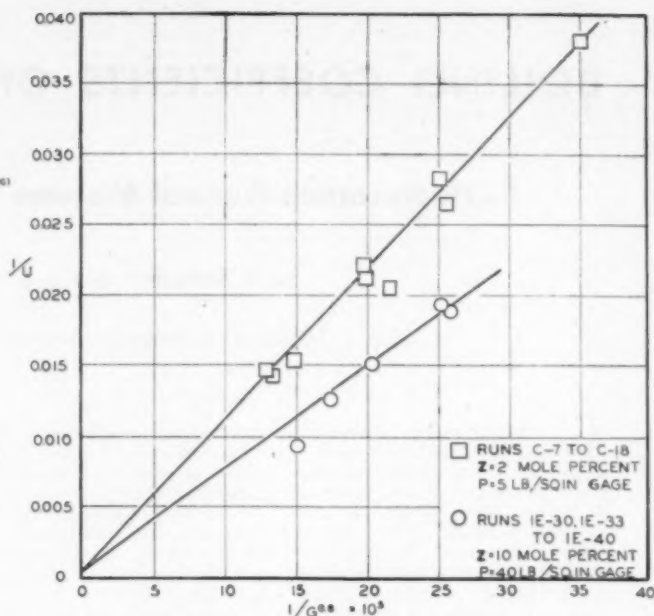
Fig. 2. Estimation of fouling by Wilson plot method (21).

Experimental

The reboiler used in this study was a vertical, once-through, forced-circulation type. A drawing is given in Figure 1. The process liquid entered the bottom head from the side, flowed upward through a bundle of 163 Admiralty metal tubes, 121⅞ in. long × ¾-in. O.D. × 14 B.W.G., and left the top head through the side. The tubes were heated on the outside by condensing steam, which entered the top of the steel shell and left the bottom as condensate. The top and bottom heads were constructed of Everdur and the tube sheets of forged aluminum bronze. The shell was insulated with 1 in. of magnesia covered with ¼ in. of asbestos cement. An extra deep stuffing box was provided to allow for movement of the bottom tube sheet due to thermal expansion of the tubes. Reboiler specifications are summarized in Table 1.

The reboiler was part of a pilot extractive distillation unit for the separation of isobutane from 1-butene with furfural as the selective solvent and has been previously described (12). This operating system was entirely closed, all streams being continu-

ously recirculated. The liquid entering the reboiler consisted of a solution of isobutane and 1-butene in furfural and this flowed by gravity from the bottom tray of the column to the reboiler for the purpose of vaporizing the dissolved C_4 hydrocarbons. The liquid-vapor mixture leaving the reboiler went to a gravity separator, from which vapor flowed to the bottom of the column. The liquid from the separator was cooled, then pumped through an orifice flowmeter to the top of the column where it entered as solvent. Since, under steady-state operating conditions, all the furfural passing through the orifice also entered the reboiler, sample analyses of the liquid at the orifice and the liquid entering the reboiler, permitted direct calculation of the flow rate of liquid entering the reboiler. The rate of pumping of solvent was controlled by a Fisher diaphragm motor valve actuated by a Brown recording flow controller connected to the standard orifice in the line. This orifice meter was previously calibrated by weighing the quantity flowing during a given time.

A standard orifice and Brown flow recorder controller was provided for the

steam to the reboiler shell. The condensate outlet was equipped with a bucket trap to maintain the liquid leaving at the saturation temperature corresponding to the pressure in the reboiler shell. The steam flow meter was calibrated by weighing the condensate and was found accurate to within ±2%.

Pressure gages were located in the reboiler process liquid line just before the entrance to the bottom head and in the process line from the reboiler to the separator just outside the top head.

Temperatures were measured by iron-constantan thermocouples in specially constructed wells which responded quickly to temperature changes (12). The couples were of 24-gage wire and the wells were made of ⅛-in. O.D. stainless steel tubing. Thermocouple potentials were read with a Brown Electronik potentiometer and certain important values were recorded continuously by a 16-point Brown Electronik strip chart recorder. The potentiometer was calibrated with a Leeds and Northrup precision potentiometer and the iron-constantan thermocouples were calibrated at the freezing and boiling points of water.

After establishment of steady state, the following data were recorded: temperatures of the reboiler process liquid inlet and outlet, temperatures of the atmosphere, steam supply, and steam condensate; pressures of the steam at the flowmeter and at the reboiler shell, and pressures of the reboiler process liquid inlet and outlet. Furfural and steam flow rates were automatically recorded. Samples were taken of the liquid entering and leaving the reboiler and of the vapor leaving in Table 2.

Sampling Procedure and Analysis. Hydrocarbon vapor samples were taken in

TABLE 1.—REBOILER SPECIFICATIONS

Part	Dimensions	Material
Shell	17-in. I.D., ½-in. wall thickness, 118¼ in. long	Steel
Main and floating heads	13⅝-in. I.D., ¼-in. wall thickness, 18 in. long	Everdur
Main tube sheet	21½-in. D., 1½ in. thick	Forged aluminum bronze
Floating tube sheet	16⅝-in. D., 2 in. thick	Forged aluminum bronze
Tubes	¾-in. O.D., 14 B.W.G., 121⅞ in. long	Admiralty metal

Total number of tubes—163
Cross-sectional area inside tubes ....43.7 sq.in. or 0.303 sq.ft.
Total outside tube heat-transfer area ....314 sq.ft.
Total inside tube heat-transfer area ....245 sq.ft.
Tube spacing:
    Equilateral triangular, 1 in. between centers
Inside tube diameter ....0.0486 ft.

glass-collecting bottles sealed with saturated sodium nitrate solution. The liquid samplers were small aluminum bombs of the type used by Mertes and Colburn (18). Silver nitrate solution catalyzed with mercuric nitrate was used to absorb the 1-butene in an Orsat-type apparatus, the isobutane being determined by difference. The liquid samples were analyzed by stripping the hydrocarbons from the furfural with carbon dioxide, absorbing the carbon dioxide in potassium hydroxide solution, and measuring the total hydrocarbon gas volume. This gas was then analyzed for isobutane and 1-butene. Analytical procedures have been previously described (18).

Materials. The furfural was of the technical grade, obtained from the Quaker Oats Co., and contained less than 0.2% water and 0.1% polymer originally. Triethanolamine was used to adjust the acidity to a pH of 6. The furfural was periodically removed for redistilling to prevent the polymer content from exceeding 1%.

The hydrocarbons were Phillips Petroleum Co.'s pure grade (specified 99% pure) and were used as purchased.

Physical Properties. Buell and Boatwright (5) have tabulated values of specific heat, thermal conductivity, density, viscosity, and latent heat of pure furfural. Density, viscosity, and specific heat of the pure hydrocarbons were obtained from available sources (2, 10, 13). Grohse (11) has utilized these data and the values of heats of solution of hydrocarbons in furfural given by Mertes and Colburn (18) to prepare an enthalpy chart for the system isobutane-1-butene-furfural. Densities and viscosities of solutions were estimated from the values for pure liquids. Compressibility factors for the gases were obtained from Olds *et al.* (19). The physical properties employed are summarized for convenience in Table 3.

Method of Calculation

Over-all Coefficients of Heat Transfer for Boiling Runs. Over-all coefficients of heat transfer were calculated by the usual relationship $Q = UA\Delta t$, based on the inside tube surface area. The heat input to the reboiler was calculated from the product of the steam flow rate and the enthalpy difference between supply and condensate. When corrected for estimated radiation loss, this figure gave the net heat transferred, which was checked against an enthalpy balance on the process fluid. Runs with discrepancies between these two values of heat flow rates greater than 10% were discarded. The average discrepancy of the data utilized was ±4.2%. Regardless of the agreement between the two values for the total heat flow rate, the value obtained from the steam rate was used in the calculations since the steam meter had been carefully calibrated and was known to be accurate. On the other hand, there is some doubt concerning the accuracy of literature values for the heat capacity of furfural at temperatures around 300° F.

The nature of the apparatus employed did not permit measurement of the process fluid temperature at any point except at the entrance and exit parts of the boiler so that some assumption was necessary for calculation of the mean temperature difference. The widely employed logarithmic mean temperature difference requires constant specific heat values for the process fluids and constant coefficients of heat transfer along the tube length. The former condition is met fairly well in this work, but it was expected that as vaporization proceeds along the tube length the coefficient of heat transfer would change appreciably. The work of previous investigators (16, 17) has shown that the coefficient of heat transfer increases with the proportion vaporized, within moderate limits. In addi-

TABLE 2.—SAMPLE OPERATING DATA FOR C₄ HYDROCARBON-FURFURAL REBOILER

Run Number	C-3	C-13	B-8	IE-30	IE-33
Temperatures, ° F.					
Process liquid entering reboiler	121	121	122	132	185
Process liquid leaving reboiler	223	222	277	297	297
Atmosphere	70	73	42	44	46
Steam entering reboiler	315	325	333	331	329
Steam shell condensate	244	253	287	310	308
Pressures, lb./sq.in.gage					
Reboiler steam shell	12	4	40	60	60
Process liquid inlet	.....	.....	.....	53	46
Process liquid outlet (12 ft. above inlet)	1.9	2.8	15	49	42
Process Liquid Analyses, Mole %					
Liquid entering reboiler					
Total C₄ hydrocarbon	0	2.61	5.95	15.40	12.03
Isobutane (furfural-free basis)	0	43.81	.....	17.02	16.95
Liquid leaving reboiler					
Total C₄ hydrocarbon	0	1.85	1.64	3.46	2.86
Isobutane (furfural-free basis)	0	54.05	.....	11.50	13.34
Flow Rates					
Steam rate, lb./hr.	704	410	1242	670	834
Liquid leaving reboiler, lb.moles/hr.	152.0	96.8	147.9	63.5	87.7

TABLE 3.—PHYSICAL PROPERTIES OF FURFURAL-C₄ HYDROCARBON SYSTEM

Enthalpy, B.t.u./lb. mole—Datum: Pure, Saturated Liquids at 32° F.

		Pure Components			Mole % Isobutane in Furfural			Mole % 1-Butene in Furfural		
		Isobutane	1-Butene	Furfural	5	10	20	5	10	20
Liquid, ° F.	100	2290	2140	2500	....	2770	3020	....	2670	2820
	150	4020	3770	4510	....	4770	5000	....	4650	4750
	200	5940	5400	6530	6680	6770	6990	6600	6640	6680
	250	.....	.....	8710	8840	....	....	8750	....	....
Vapor, ° F.	100	10700	11000	24700						
(0 lb./sq.in.abs.)	150	11980	12120	25950						
	200	13250	13240	27200						
	250	14650	14400	28600						
(65 lb./sq.in.abs.)	100	10110	10490							
	150	11500	11660							
	200	12950	12900							
	250	14400	14150							

| | | Pure Furfural | | | | Mole % 1-Butene or Isobutane in Furfural | | | | | | |
| | | | | | | 6 | | | | 12 | | |
	100° F.	150° F.	200° F.	250° F.	100° F.	150° F.	200° F.	250° F.	100° F.	150° F.	200° F.	250° F.
Viscosity, cp.	1.222	0.852	0.641	0.527	1.076	0.741	0.560	0.457	0.918	0.637	0.482	0.400
N_{Pr} (Prandtl number)	7.95	5.70	4.43	3.97	6.94	4.94	3.85	3.38	5.98	4.24	3.33	2.86
Specific heat B.t.u./(lb.) (° F.)	0.408	0.423	0.437	0.453	0.406	0.420	0.434	0.450	0.406	0.419	0.433	0.449
Density g./cc.	1.140	1.110	1.080	1.049	1.108	1.070	1.032	0.994	1.065	1.026	0.987	0.948

| | | Furfural | | | | Isobutane | | | | 1 Butene | | |
	100° F.	150° F.	200° F.	250° F.	100° F.	150° F.	200° F.	250° F.	100° F.	150° F.	200° F.	250° F.
Vapor pressure mm. Hg.	5.9	24.7	81.5	214	3720	7399	13260	21890	3181	6478	11840	19890

Thermal conductivity of furfural, $k = 0.1525$ B.t.u./(sq.ft.)(hr.)(° F.)/ft.
Coefficient of thermal expansion of furfural, $\beta = 0.000576$ per ° F.
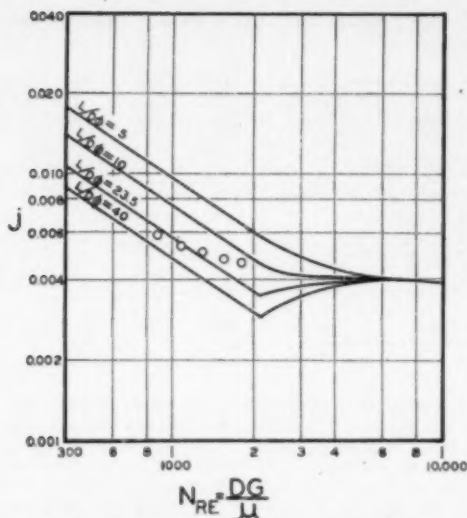
Fig. 3. Comparison of nonboiling data for heating of pure furfural with correlation of Colburn (8). Solid lines represent the equation $j = 1.86 \ (L/D\phi)^{-\frac{1}{3}} \ (N_{Re})^{-\frac{2}{3}}$, where $\phi = (\mu/\mu_s)^{\frac{1}{3}}(1 + 0.015 \ N_{Gr}^{\frac{1}{3}})$. Value of $(L/D\phi)$ in this study was 23.5.

tion, the temperature rise of the process liquid in the reboiler is about 150° F., which causes a change in the physical properties of the liquid, especially the viscosity. This latter effect is somewhat counterbalanced by the loss of the low viscosity C_4 hydrocarbons from the liquid, but the net result of the temperature change is to increase the coefficient of heat transfer.

Colburn (7) has shown that when the coefficient of heat transfer is assumed to vary linearly with temperature, the use of a logarithmic mean driving force is permissible if the coefficient of heat transfer so obtained is associated with a mean bulk temperature of the liquid t_m given by the equation:

$$t_m = F(t_2 - t_1) + t_1 \qquad (1)$$

where

$$F = \frac{1/C + \dfrac{R}{R-1}}{1 + \dfrac{\log{(C+1)}}{\log R}} - 1/C$$
$$(2)$$

and

$$R = \Delta t_1 / \Delta t_2 \qquad (3)$$
$$C = (U_2 - U_1)/U_2 \qquad (4)$$

Although applicability of the above relationships could not be tested for the present case, these equations were employed in the calculations since they hold fairly well for nonlinear cases and are much to be preferred over those providing no allowance for change in the coefficient of heat transfer. Equation (4) required knowledge of the relative magnitudes of the local coefficients of heat transfer at the two ends of the tube, and such information was not available. A value of C was assumed to be 2. Actually an estimate of the value of C is permissible since the equations are not too sensitive to changes in this value.

Evaluation of the heat-transfer coefficient by integration methods utilizing successive small sections of the tube length over which the mean temperature difference is closely equal to the log mean value would be more precise than the above-given method if the corresponding quantity of heat transferred in each small section could be accurately determined. Unfortunately, with the ternary mixture used in these studies, known assumed values of temperature and pressure at such intervals along the tube length will not permit ready calculation of vapor and liquid quantities even when equilibrium of vapor and liquid is assumed. Treatment of the two C_4 hydrocarbon components as a single substance enables a good approximation to be made, but even in this case equilibrium data must be estimated above 200° F. Lack of precise enthalpy data for C_4 hydrocarbon-furfural mixtures at higher temperatures further limits the accuracy obtainable from such methods.

Evaluation of Individual Film Coefficients. Two series of the boiling runs

are available where all conditions except the process fluid flow rate were held reasonably constant so that the Wilson plot method (21) could be applied to evaluate the combined steam, metal wall, and fouling resistances. In runs C-7 through C-18, average conditions were as follows: entering and leaving process liquid temperatures, 123° and 221° F., respectively; shell-side steam temperature, 238° F.; outlet pressure of the process fluid, 5 lb./sq.in. gage; and 2 mole % of the inlet liquid was vaporized in the reboiler. In runs IE 30 and 33-40, the entering and leaving process liquid temperatures were 135° and 295° F., respectively; the shell-side steam temperature was 307° F.; the outlet pressure of the process fluid was 40 lb./sq.in. gage; and 10 mole % of the inlet liquid was vaporized in the reboiler.

As will be shown later, the process-side boiling coefficient of heat transfer varied as the 0.8 power of the mass velocity of the fluid inside the tubes, so that the relationship $1/U = 1/h_e + 1/(aG^{0.8})$ is applicable for any series of runs where G is the only variable. In this equation U is the measured over-all heat-transfer coefficient, $1/h_e$ is the combined steam, metal, and fouling resistances, and a is a constant. Figure 2 is a plot of experimental values of $1/U$ for the two series of runs mentioned above plotted against $1/G^{0.8}$, where it may be seen that two separate straight lines are obtained. Some question as to the exact placing of these lines is evident, but in any case the magnitude of the y-intercept is small. This appears reasonable in view of the small resistance of the metal wall and probable absence of appreciable fouling. Although visual inspection of the tubes has not been made following these tests, an examination of a portion of the interior of the Everdur top head was made. No noticeable fouling of this metal was observed after a total of 600 hr. of operation.

Calculation of the boiling film coefficients of heat transfer was made for all runs by subtracting from the over-all resistance a value of $1/h_e$ of 0.0005. Since around 95% of the total resistance is represented by the boiling coefficient, small uncertainty in evaluating the intercept $1/h_e$ on the Wilson plot of Figure 2 would not cause appreciable error in the experimental value for the boiling coefficients.

A sample calculation for run IE-33 is given in detail on page 155.

Coefficients for Non-Boiling Runs. A series of runs was made heating pure furfural inside the tubes in which no boiling occurred. These runs were made to compare results with the accepted

Furfural composition in the vapor at reboiler exit
Vapor pressure of furfural at exit temperature of 297° F. (Table 3), 501 mm. Hg.
Furfural composition of liquid at reboiler exit (Table 2) .... 97.12 mole %
Total pressure of system at reboiler exit (Table 2)
42 lb./sq.in. gage or .... 2930 mm. Hg. abs.
Furfural composition in the vapor at reboiler exit (Table 2)
$$(501)(97.12)/2930 = 16.6 \text{ mole } \%$$

Flow rates of process fluids
Process liquid at reboiler exit (Table 2) .... 87.7 lb.moles/hr.
Furfural composition of liquid at reboiler entrance (Table 2) .... 87.97 mole %
Furfural composition of liquid at reboiler exit (Table 2) .... 97.12 mole %
Furfural composition of vapor at reboiler exit (Table 2) .... 16.6 mole %

Writing the equation that the total moles of furfural entering the reboiler equals the sum of the moles of furfural leaving the reboiler as vapor plus the moles of furfural leaving as liquid, and letting V = total moles of vapor leaving the reboiler

$$(87.7 + V)(0.8797) = (V)(0.166) + (87.7)(0.9712)$$
$$V = 11.2 \text{ lb.moles/hr.}$$

Vapor leaving reboiler = 11.2 lb.moles/hr. at 295° F. and avg. mole wt. of 92.4
Process liquid entering reboiler = 87.7 + 11.2 = 98.9 lb.moles/hr.

Volume of process fluids at reboiler exit
Vapor volume:
Vapor leaving reboiler : 11.2 lb.moles/hr. at 295° F. and 40.0 lb./sq.in. gage or (14)
Compressibility factor of vapor (19) 0.945
Volume of vapor leaving reboiler
$$(11.2)(359)(0.945)(755/492)(147/54.7) = 1530 \text{ cu.ft./hr.}$$

Liquid volume
Liquid leaving reboiler : 87.7 lb.moles/hr. at 295° F. and avg. mole wt. of 92.4
Density of liquid (Table 3) 1.001 g./cc.
Volume of liquid leaving reboiler
$$(87.7)(92.4)/(1.001)(62.4) = 1301 \text{ cu.ft./hr.}$$

Ratio of gas to liquid volume at reboiler exit .... 1530/1301 = 11.8

Heat input supplied by steam to process fluid
Steam flow rate (Table 2) .... 834 lb./hr.
Enthalpy of steam entering reboiler at 325° F. and 60 lb./sq.in. gage (14) .... 1,195 B.t.u./lb.
Enthalpy of steam condensate leaving reboiler at 308° F. and 60 lb./ sq.in. gage (14) .... 278 B.t.u./lb.
Total heat lost by steam in reboiler shell:
834(1195-278) = 764,000 B.t.u./hr.
Heat lost from reboiler shell and head by convection and radiation to atmosphere, (based on thermal conductivity of insulation of 0.040 B.t.u./(hr.)(sq.ft.)(°F.)/(ft.) and free convection and radiation coefficient of 2.0 B.t.u./(hr.)(sq.ft.)(°F.) for insulated surfaces and 4.0 B.t.u./(hr.)(sq.ft.)(°F.) for bare metal surfaces) .... 5,490 B.t.u./hr.
Net heat transferred by steam to process fluid = 764,000 − 5,490 = 759,000 B.t.u./hr.
Per cent of steam input heat lost by radiation and free convection to atmosphere .... 0.7 %

Heat input gained by process fluid through reboiler
This calculation was made using the enthalpies of Table 3, by subtraction of enthalpy of feed from total enthalpy of the exit streams. Heats of mixing of the gases were neglected. In tabular form, for the sample run:

Exit Streams: Composent	Flow Rate, lb. moles/hr.	Enthalpy B.t.u./lb. mole	Total Heat, B.t.u./hr.
Liquid solution	87.7	10,900	956,800
Furfural vapor	1.9	56,800	
Isobutane vapor	2.0	55,900	
1-Butene vapor	7.3	51,600	
		112,200	1,156,800 B.t.u./hr.
Feed:			
Liquid solution	98.9	4,150	411,000
Difference			745,800 B.t.u./hr.

Over-all heat gained by process fluid:
Heat input gained by process fluid, 745,800 B.t.u./hr.
Per cent deviation from heat lost by steam to process fluid, 1.7% low.

Over-all log mean temperature difference:
Δt_a (top of reboiler) = 308 − 297 = 11° F.
Δt_b (bottom of reboiler) = 308 − 135 = 173° F.

$$\Delta t_m = \frac{\Delta t_b - \Delta t_a}{2.3 \log \Delta t_b / \Delta t_a} = \frac{173 - 11}{2.3 \log 173/11} = 59.6° \text{ F.}$$

Over-all heat-transfer coefficient
Inside heat-transfer area (Table 1) .... 245 sq.ft.
Over-all heat-transfer coefficient,
$$U = Q/A\Delta t_m = 759,000/(245)(59.6) = 52.0 \text{ B.t.u./(hr.)(sq.ft.)(°F.)}$$

Mass velocity inside tubes:
Mass rate of flow (from above) .... 98.9 lb.moles/hr.
Avg. mole wt. of process fluid .... 92.4 lb./lb.mole
Inside cross-sectional area of tubes (Table 1) .... 0.303 sq.ft.
Mass velocity,
$$G = (92.4)(98.9)/0.303 = 30,100 \text{ lb./(hr.)(sq.ft.)}$$

Boiling film coefficient:
Boiling film coefficient, h_b, combined steam film, metal wall, and fouling resistances (Fig. 2) .... 2000 B.t.u./(hr.)(sq.ft.)(°F.)
h_b, boiling film coefficient,
$$= 1/(1/U - 1/h_b)$$
$$= 1/(1/52.0 - 1/2000)$$
$$= 53.2 \text{ B.t.u./(hr.)(sq.ft.)(°F.)}$$

Calculation of dimensionless groups. Dimensionless groups are evaluated for liquid at mean liquid composition and mean liquid bulk temperature.

Mean liquid composition:
Inlet liquid composition (Table 2) .... 12.03 mole % C₄ hydrocarbon
Outlet liquid composition (Table 2) .... 2.88 mole % C₄ hydrocarbon
Mean liquid composition
$$(12.03 + 2.88)/2 = 7.46 \text{ mole } \% \text{ C}_4 \text{ hydrocarbon}$$

Mean liquid bulk temperature
By Eq. (3), $R = \Delta v/\Delta v_0 = 173/11 = 15.7°$ F.
Assume C in Eq. (2) = 2
By Eq. (2), $F = 0.62$
By Eq. (1), t_m, the mean liquid bulk temperature = $F(t_2 - t_1) + t_1 = 0.62(297 - 135) + 135 = 235°$ F.
(If C had been assumed equal to 3, $t_m = 232°$ F.; if t_m had been assumed equal to $(t_1 + t_2)/2$, $t_m = 216°$ F.)

Prandtl Number, N_{Pr} (Table 3) 3.52
Nusselt number, hD/k
Inside tube diameter (Table 1) .... 0.0486 ft.
Thermal conductivity of liquid (Table 3) .... 0.1525 B.t.u./ (sq.ft.)(°F./)(ft.)

$$hD/k = (53.2)(0.0486)/0.1525 = 17.0$$

Reynolds number, DG/μ
Viscosity of liquid, μ (Table 3) .... 0.454 cp.
$$DG/\mu = (0.0486)(30,100)/(0.454)(2.42) = 1330$$

equation of Colburn (8) for heating fluids inside horizontal tubes in viscous flow. Computed values of the resulting coefficients of heat transfer are plotted as points on Figure 3. On the same figure predicted curves (8) are given for viscous flow inside tubes where natural convection effects are appreciable. The parameter on Figure 3, $L/(D\phi)$, represents the length to diameter ratio of the tube divided by a factor ϕ which takes into account natural convection effects and which has a value of 23.5 for these runs. The predicted line appears to correlate the data in a satisfactory manner except that no sharp break in the experimental points at the transition region between viscous and turbulent flow was obtained. The agreement obtained between predicted and experimental results confirms the experimental methods and physical property data employed. The absence of fouling predicted by the Wilson plot curves of Figure 2 for the boiling runs is also confirmed by these data. A sample calculation for nonboiling run C-3 is outlined below:

the same position on the graph. Rather, it appears that the volume of vapor produced is the principal factor controlling the increase in performance, so that the total pressure must be considered, as well as the fraction vaporized. Thus the runs in which 5 mole % of the feed was vaporized at 2 atm. total pressure produced about the same volume of vapor as the runs in which 10 to 12 mole % of the feed was vaporized at 4.3 atm. total pressure. It would apparently be more consistent to express results in terms of a parameter V/L, defined as the ratio of the volume of vapor produced to the volume of liquid remaining at the reboiler exit. Since the amount of vaporization along the tube length was not determined, correlation of results in terms of the exit vapor to liquid ratio was necessary.

A general correlation of the boiling film coefficient of heat-transfer results involving some modification of the accepted heat-transfer equations would appear desirable. Since at most only 12 mole % of the liquid was vaporized

correlated by some modification of the usual relationship for heat transfer to single-phase fluids. The need for modification would no doubt exist since local boiling effects could be great enough to induce turbulent flow characteristics in all the liquid in the tubes even though Reynolds numbers were mostly below 2000.

The accepted equation for the ordinary case of heating single-phase turbulent fluids inside tubes (15) is given by

$$(hD/k)/(c\mu/k)^{0.4} = 0.023(DG/\mu)^{0.8} \tag{5}$$

This equation is plotted as a dashed line in Figure 5, where it has been extended down into the region below $N_{Re} = 2000$ where most of the experimental data lie. Plotted on the same figure are the experimental points of this study, with the vapor-liquid volume ratio at the reboiler exit introduced as parameter beside each point as just discussed. In Figure 5, the physical properties of viscosity, thermal conductivity, and heat capacity were evaluated as liquid properties at the average composition of the liquid and at the mean bulk temperature of the liquid as computed by Equations (1-4).

The Nusselt-type correlation was chosen since mass velocity appears as a variable only in the Reynolds number, and, as will be shown later, a modification of the mass velocity is required to locate the final parameter lines on Figure 5. The more commonly used j-factor vs. Reynolds number type of plot (15) contains the mass velocity as a variable in both the ordinate and abscissa variables and thus would be less desirable for the present case.

Since the exact location of the proper parameter lines is not too clear from Figure 5, a plot was made in which the degree of turbulence for each boiling run was expressed in terms of an effective mass velocity, G'. This mass velocity is defined as that value required to give the same heat-transfer characteristics as represented by the $(hD/k)/(c\mu/k)^{0.4}$ group for the heating of the liquid without boiling, as was actually obtained for the boiling run considered. Obviously the values of G' for the boiling runs would be greater than the values of G, the actual mass velocity, although the two values would approach each other as the amount of boiling approaches zero. Values of G' for each experimental run were computed as that value of mass velocity required by Equation (5) to predict the actual value of $(hD/k)/(c\mu/k)^{0.4}$ obtained experimentally.

In Figure 6 values of G'/G are plotted against the vapor-liquid volume at the reboiler exit as a means of comparing the increase in turbulence incited

Calculation of the heat-transfer coefficients was carried out similarly as the example for run IE-33, except that results were also computed by using an over-all arithmetic mean temperature difference, Δt_a, to be consistent with the Colburn correlation (8):

$$\Delta t_a = (\Delta t_1 + \Delta t_b)/2 = (173 + 11)/2 = 92° \text{ F.}$$

Dimensionless groups. These were evaluated at the mean film temperature, t_f, which was taken to be greater than the mean bulk temperature of the liquid by one-fourth the difference between the mean bulk temperature and the wall temperature.

Mean bulk temperature, t_m, by methods illustrated above. .179° F.
Wall temperature, t_w, assumed equal to the saturation
   temperature of the steam (Table 2) ....244° F.
Mean film temperature,
   $t_f = t_m + (t_w - t_m)/4 = 179 + (244 - 179)/4 = 195°$ F.
j-factor, $(h/cG)(N_{Pr})^{2/3}$
   Film coefficient, h, based on Δt_a, (Table 4) ....35.7 B.t.u./(hr.)(sq.ft.)(° F.)
   Liquid heat capacity at mean film temperature (Table
   3) ....0.424 B.t.u./(lb.)(° F.)
   Mass velocity inside tubes (Table 4) ....48,150 lb./(hr.)(sq.ft.)
   Prandtl number, N_{Pr} (Table 3) 4.94
   j-factor, $(h/cG)(N_{Pr})^{2/3}$
      $(35.7)(4.94)^{2/3}/(0.424)(48,150) = 0.00508$
   Reynolds number, DG/μ
   Viscosity of liquid at mean film temperature, (Table
   3) ....0.68 cp.
   Reynolds number, DG/μ
      $(0.0486)(48,150)/(0.68)(2.42) = 1297$

Results

Experimental boiling coefficients of heat transfer are plotted in Figure 4 as a function of the mass velocity inside the tubes. Plotted beside each experimental point is the mole fraction of entering feed which is vaporized. Also plotted on this figure are the nonboiling data for the heating of pure furfural. It is seen from this figure that at any value of mass velocity the coefficient of heat transfer is increased when boiling is present. The amount of the increase in the boiling coefficient is not a simple function of the fraction vaporized, however, since the points for approximately 5 and 10 mole % vaporized lie in about

due to the presence in the liquid mixture of large amounts of relatively nonvolatile furfural, the full degree of turbulence associated with free boiling of a pure substance was probably not present. Also, although the liquid entered at its bubble point in the boiling runs, vaporization of the small amount of C_4 hydrocarbons present raised the boiling temperature by 100° to 150° F. Thus only around 25% of the total heat transferred actually was used to effect vaporization; the remainder was used to raise the temperature of the unvaporized liquid. This means that the magnitude of the coefficient of heat transfer probably was not entirely controlled by the boiling process, but could perhaps be

Fig. 4. Observed process film heat-transfer coefficients as a function of mass velocity. Numbers beside points refer to mole per cent of reboiler feed vaporized.
□ — Approximately 2 mole % of feed vaporized, 5 lbs./(sq.in.) gage reboiler outlet pressure.
▽ — Approximately 5 mole % of feed vaporized, 15 (lbs.)/(sq.in.) gage reboiler outlet pressure.
○ — Approximately 10 mole % of feed vaporized, 40-60 (lbs./(sq.in) gage reboiler outlet pressure.
+ — Heating of pure furfural without boiling. (h values based on arith. mean Δt for these runs only).

Fig. 5. Final correlation of boiling data. Dashed line is an extrapolation of Eq. (5), accepted correlation (15) for heat transfer to liquids in turbulent flow inside tubes without phase change. Solid lines represent even values of the parameter (V/L), the reboiler exit vapor-liquid volume ratio. Numbers beside points refer to actual values of this parameter. Symbols as on Fig. 4.

by the boiling expressed by the ratio G'/G as a function of the vapor-liquid volume. From this figure the data appear to be well correlated by a straight line starting at a vapor-to-liquid-volume ratio of zero, with random variations of about ±10% on either side of the line not showing any trend with the various operating conditions represented. The straight line correlation of the variable G'/G with the vapor-liquid ratio shows that each parameter line on the log-log plot of Figure 5 will be straight and parallel to the basic line of Equation (5) where the vapor-liquid ratio is zero. For example (from Fig. 6) where the vapor-liquid ratio is 5, the corresponding value of G'/G is 1.33. To locate a line on Figure 5 with a parameter value of $V/L = 5$, at each chosen value of the group $(hD/k)/(c\mu/k)^{0.4}$ the ratio of the Reynolds number from Equation (5) to the Reynolds number for the desired parameter line will be the constant, 1.33. If the ratio of the two Reynolds numbers is constant at any value of $(hD/k)/(c\mu/k)^{0.4}$, then the horizontal distance between them on the log-log plot of Figure 5 will be constant, so that each parameter line also has a slope of 0.8. This slope indicates that turbulent flow characteristics were present in the reboiler tubes down to a Reynolds number of 600, the lowest value studied.

An alternate treatment of the results would be to plot the group $(hD/k)/(c\mu/k)^{0.4}$ as a function of DG'/μ with G' defined as above. The term DG'/μ is equivalent to $(DG/\mu)e^{0.057(V/L)}$ since the straight line of Figure 6 may be expressed by the equation $ln\ G'/G = 0.057(V/L)$. Such a plot brings all the experimental points onto the single line defined by Equation (5) with the scattering of points about the same as obtained in Figure 6.

Comparison of Results with Data of McAdams, Woods, and Heroman (17). As mentioned earlier, McAdams, *et al.*, measured heat-transfer coefficients for the case of vaporizing benzene from benzene-oil mixtures inside of horizontal tube sections. The benzene-oil mixture used was similar to that employed in the present case since it was composed also of substances of widely different volatility. Direct comparison of their data with those of this study is not too satisfactory because the amounts of vapor generated in the benzene-oil studies were quite large. A comparison is shown here, however, for a few pertinent runs.

The apparatus employed by McAdams, *et al.*, was made up from 1-in. diameter copper pipe formed into four horizontal sections which were connected by return bends. Each straight section was 9 ft.-6 in. long, and was heated by three steam jackets

each 3 ft.-2 in. long. Measurement of the steam used in each jacket permitted calculation of the progressive change in heat-transfer coefficient from jacket to jacket. In runs *BO-2* and *BO-3* the benzene-oil mixture entered jacket 2 just as boiling commenced, and left the jacket after about 10 wt. % of the entering feed had been vaporized, corresponding to an exit vapor-liquid volume ratio, V/L, of 35.6. For these two runs, the exact values of G'/G, having the same significance and calculated in the same manner as the runs of this paper, were equal to 10.0 and 10.7 respectively. Referring to Figure 6, these values of both V/L and G'/G are much greater than those experienced in this study, but if the straight line of Figure 6 is extended to a value of V/L of 35.6, the resulting
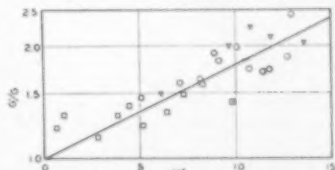
Fig. 6. Means of locating parameter lines of Fig. 5. The increase in performance during boiling, G'/G, expressed as function of parameter (V/L), the reboiler exit vapor-liquid volume ratio. G' is a hypothetical mass velocity, which, when used in the correlation for heat transfer to nonboiling liquids in turbulent flow inside tubes (Eq.(5)), will predict a coefficient of heat transfer equal to that actually observed during boiling at the true mass velocity, G. Symbols as on Fig. 4.

TABLE 4.—SAMPLE RESULTS FOR C₄ HYDROCARBON-FURFURAL REBOILER

Run Number	O-3	O-13	S-3	IE-30	IE-33
Logarithmic mean temp. diff., neglecting steam superheat, ° F. ..	58.7	42.5	55.4	63.0	59.6
Arithmetic mean temp. diff., ° F.	72.7	......	......	......	......
Mean bulk temp., ° F., by Eq. (1)	178.6	183.9	225.	287.	239.
Flow rates					
Process liquid entering reboiler, lb.moles/hr.	152.9	97.1	156.9	74.4	98.9
Process vapor leaving reboiler, lb.moles/hr.	......	0.26	8.99	10.9	11.2
Vapor-liquid volume ratio at reboiler exit	......	0.75	10.5	16.1	11.8
Heat transferred, B.t.u./hr. × 10⁻³					
Based on steam rate, corr. for radiation	635.	373.	1167.	608.	759.
Based on process fluid enthalpy rise	631.	393.	1153.	584.	746.
Discrepancy based on steam, %	0.6	—5.1	0.6	3.9	1.7
Heat-transfer coefficient, B.t.u./(hr.) (sq.ft.) (° F.)					
Overall coefficient					
Based on log mean Δt	44.5	37.6	56.0	39.5	52.0
Based on arith. mean Δt	35.7	......	......	......	......
Process film coefficient					
Based on log mean Δt	45.4	39.5	90.0	49.2	53.2
Based on arith. mean Δt	36.2	......	......	......	......
Mass velocity of process fluid inside tubes, lb./(hr.)(sq.ft.)	48,150	30,600	48,800	22,700	30,100
Reynolds number inside tubes, based on liq. phys. properties at mean bulk temp.	1297	963	1766	1007	1330
(hD/k)/(cμ/k)³·⁴	......	7.28	17.52	8.50	11.16
f-factor	0.00506	......	......	......	......
Ratio of effective mass velocity to actual mass velocity	......	1.219	2.24	1.610	1.729

predicted value of G'/G is 8.3. Such agreement is fairly good considering the extrapolation involved. However, it is questionable whether the McAdams' data should be predicted by the methods of this paper since these methods were derived for cases of small vaporization and are based upon liquid properties. No data are available from the work of McAdams, et al., for the case of smaller amounts of vaporization than those given here. This is due to the fact that all their runs were carried out at atmospheric pressure so that even with small weights of benzene vaporized, the volume of vapor produced was larger than any runs of this study where elevated operating pressures accompanied large weights vaporized.

Conclusions

Results of this paper show the order of magnitude of the increase in boiling coefficients of heat transfer which can be expected with increasing vaporization of small amounts of a volatile component from a mixture containing large amounts of a slightly volatile component. The vaporization caused an increase in both the turbulence and in the boiling temperature of the remaining liquid, the latter effect being so large that it required a large fraction of the heat being transferred. A correlation of the results of this study showed that under the conditions of variable total pressure the volume of vapor generated was the factor affecting increase in the coefficient of heat transfer. More fundamental studies in which local boiling coefficients are measured along the tube length are greatly to be desired to provide basic reboiler design information.

Acknowledgment

Notation

A = area, sq.ft.
c = specific heat, B.t.u./(lb.) (° F.)
$C = (U_2 - U_1)/U_2$
D = internal tube diameter, ft.
$F = (t_m - t_1)/(t_2 - t_1)$
G = mass velocity, lb./(hr.) (sq.ft.)
G' = effective mass velocity, lb./ (hr.) (sq.ft.)
h = film heat-transfer coefficient inside tubes, B.t.u./(hr.) (sq.ft.) (° F.)
h_c = combined fouling, steam, and metal wall coefficient, B.t.u./ (hr.) (sq.ft.) (° F.)
j = liquid film transfer factor, $(h/cG)(N_{Pr})^{⅔}$
k = thermal conductivity, B.t.u./ (hr.) (sq.ft.) (° F.)/ft.
Q = total heat transferred, B.t.u./ hr.
$R = \Delta t_1/\Delta t_2$
t_1 = reboiler process inlet temperature, ° F.
t_2 = reboiler process outlet temperature, ° F.
t_f = mean film temperature, defined as $t_m + (t_w - t_m)/4$, ° F.
t_m = mean bulk temperature, ° F.
t_w = wall temperature, ° F.
Δt_1 = temperature difference at reboiler inlet, ° F.
Δt_2 = temperature difference at reboiler outlet, ° F.
Δt_a = arithmetic mean temperature difference, ° F.
Δt_m = logarithmic mean temperature difference, ° F.
U = over-all coefficient, B.t.u./ (hr.) (sq.ft.) (° F.)
μ = viscosity, lb./(ft.) (hr.) or cp.
N_{Nu} = Nusselt number, hD/k
N_{Pr} = Prandtl number, $c\mu/k$
N_{Re} = Reynolds number, DG/μ
N_{Gr} = Grashof number, (8)
Z = mole fraction of reboiler feed vaporized
V/L = reboiler exit vapor to liquid volume ratio

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(Presented at Boston (Mass.) Meeting.)

The picture above shows downtown Kansas City, Mo., looking north toward the business district. The Liberty Memorial and Mall, honoring the heroes of World War I, is shown in the near foreground, directly south of the Union Station, fourth largest in the world. Across the Missouri River, in the background is the Municipal Air Terminal and beyond it the Fairfax Airport, Kansas City, Kan.

Courtesy of Trans World Airline

KANSAS CITY MEETING

May 13-16, 1951

WILLIAM W. NIVEN, JR.

Midwest Research Institute, Kansas City, Missouri

A MIDWEST Meeting of the A.I.Ch.E. will be held in the Heart of America on May 13-16, with the Kansas City Section playing host. Symposia on plant management and engineering and on ammonia synthesis will highlight the program. Several papers will be devoted to petroleum refining and will range from light hydrocarbon recovery to refinery residue processes. General subjects to be dis-

Left to right: H. H. Young, chairman, Hotel and Meeting Room Reservations Committee; J. R. Salsbury, chairman, Printing Committee; H. A. Hopmann, chairman, Plant Trips Committee, and L. E. Colburn, chairman, Registration Committee.

William Rockhill Nelson Gallery of Art and Mary Atkins Museum of Fine Arts, Kansas City, home of a collection containing more than seven and one-half million dollars worth of paintings and objects of art.

Courtesy of Chamber of Commerce

cussed on the program include radio-active tracers, fractionating trays, heat exchange, fluidization, and corn milling and refining.

The broad scope of the program and Kansas City's central geographical location are expected to draw a large attendance to the meeting. Meeting headquarters will be located in the Hotel President. The committee for hotel reservations already has been functioning for more than a year to assure adequate accommodations for guests.

The May meeting will be a "tooth-cutting" venture for the two-year-old Kansas City Section. Establishment of the section in 1949 attests to the extent the industrial development has progressed in the area. The section presently has an approximate membership of 80, including about 50 members of the national organization.

Kansas City and adjacent Independence, Mo., have played an important roll in the history of the West as outfitters and final jumping-off points for the great western migration of the 1800's. Kansas City celebrated its centennial anniversary last year. The 1950 census shows a population of 453,000 for the city and 808,243 for the metropolitan area.

The agricultural economy of Kansas City is primarily that of wheat, corn, and livestock. The "bread basket of the world" lies immediately to the west, with the state of Kansas leading the nation in wheat production. The leading corn-producing state Iowa, lies immediately to the north. For the nation, Kansas City ranks second in grain-elevator capacity, second in flour production, first as a cattle market, and second as a railroad center. Its industrial and commercial activity is illustrated by the fact that it ranks eighth in bank clearings, while only seventeenth in population.

From a predominately agricultural economy, Kansas City and the Midwest are going all out for a more opportune balance between agriculture and industry. A striking lesson was learned during World War II when it was proved on a large scale that the Midwest has the resources, facilities, and manpower required for heavy industry. Industries already well established in the area, in addition to those founded on agricultural materials, include petroleum refining, synthetic ammonia and ammonium nitrate, soaps and detergents, salt refining, fertilizers, paints and varnishes, metals smelting and refining, and many others. New industrial development is progressing rapidly for more effective utilization of both agricultural materials and natural resources in the area. This development is pointed to such large-scale resources as liquid hydrocarbons, natural gas, coal, salt, clays, gypsum, and zinc and lead ores.

Progressive chemical engineering departments at Kansas State College, the University of Kansas, and the University of Missouri, provide for the Kansas City area an excellent balance between academic and industrial interests. Midwestern industry, and particularly those interested in the advancement of this industry, are fortunate in having available in Kansas City the facilities of the Linda Hall Library of Science and Technology and Midwest Research Institute. With a current catalogue of more than 3,200 technical periodicals

Below, left to right: L. V. Sorg, chairman, Entertainment Committee; Mrs. L. V. Sorg, chairman, Ladies' Program Committee; L. S. DeAtley, chairman, Publicity Committee; H. M. Steininger, co-chairman, meeting; I. E. Miller, secretary-treasurer, meeting, and C. W. Nofsinger, chairman, meeting.

THE CHEMICAL ENGINEER AND ATOMIC ENERGY

ALVIN M. WEINBERG

Research Director, Oak Ridge National Laboratory, Oak Ridge, Tennessee

AS a former theoretical physicist, I feel at ease addressing a group of chemical engineers, since in my observation I detect a striking resemblance between these two breeds—both the theoretical physicist and the chemical engineer are willing to try to do anything—and both are convinced that they *can* do anything.

I should like to trace those historical and logical threads in atomic energy development which have made the chemical engineer a key figure in the progress of the art; and I shall try further to show why I believe that the chemical engineer, by attitude and by training is the likely heir in the atomic energy business, to the mantle which the theoretical physicist, ever bent on higher and deeper truth—*i.e.*, ever with his head in the clouds—is in process of letting fall. I shall confine my remarks primarily to the reactor part of atomic energy—partly because I know most about it, and partly because it is the part of the business on whose success the whole effort will ultimately stand or fall.

When Eugene Wigner, who by the way was trained as a chemical engineer, first conceived the notion of a water-cooled chain reactor as the appropriate type for construction at Hanford early in 1942, he soon realized that the slightly long-haired and wet-eared theoretical physicists (including me) around him were hardly practical enough or generally knowing enough to make the kind of engineering decisions which were needed to reduce his brilliant conception into practice. None of us had ever seen a high pressure pump, let alone understand how a cooling tower worked. And so Lee Ohlinger, a mechanical engineer at Standard of Indiana, who by long contact with chemical engineers and chemists had practically become a chemical engineer himself, joined the small crew on the fourth floor of Eckhart Hall in Chicago to help design the Hanford reactor. Shortly thereafter, Miles Leverett, who had the distinction with T. Moore of making the first engineering design of a high-powered chain reactor—the helium cooled system—joined the group. It was this small group which included three chemical engineers that carried out the original design of the Hanford reactors. The design was worked out in detail by the Du Pont Co., and the predominantly

chemical cast given to the business by Du Pont has persisted ever since.

That the plutonium project would require chemists, and also chemical engineers, was dimly perceived even by the physicists who ran the show in the early days. For the process of dumping the spent slugs and recovering the transmuted Pu evidently involved chemical operations and chemical engineering problems of a sort made particularly sticky by radioactivity and the necessity for remote operation. In some sense, therefore, it was natural that chemical engineers were predominantly available for the seemingly nonchemical parts of the project—the reactor. Many were around because of the obviously chemical problems and when the totally new reactor engineering became necessary, the chemical engineers who were on hand naturally were pressed into service.

But this is not the only reason that chemical engineering is the dominant engineering in atomic energy. I think it is so also because reactor engineering requires a broad synthesis, a knowledge of many different kinds of scientific discipline, and it is my impression that chemical engineers because of their training and their conviction that they can do anything are among the few engineers with breadth of view sufficient to meet situations as novel as those encountered in a high-powered chain reactor.

In a chain reactor the situation is, as is generally known, novel indeed. While the chain reaction itself is a matter for the nuclear physicist, the chain reactor, involving chemical and metallurgical materials whose properties are subject to stress either from radiation or from high temperature, is primarily a chemical system. In fact, as the demands for higher temperatures in chain reactors increase, the demands on materials are bound to increase also and the requirements for engineers who have a feeling for materials are likely to grow greater correspondingly.

Thus to summarize, reactor engineering, in its broadest sense, appeals particularly to chemical engineers, and is appealing to them for the following reasons:

1. It requires versatility and breadth of viewpoint.
2. It places demands on materials and therefore requires knowledge and feeling for materials.

3. It always involves chemical operations and therefore requires engineers with chemical background.

If one examines the current atomic energy program it is apparent, and indeed striking, to what degree reactor technology is becoming a predominantly chemical technology. Of the two major long-term objectives of atomic energy—production of cheap fissionable material with power as a by-product, and extraction of high-temperature heat from a mobile system—both involve chemistry in the most crucial manner. Thus the production of fissionable material by the breeding principle in the Experimental Breeder Reactor at Arco, involves the most accurate kind of chemical bookkeeping if more fissionable atoms are to be produced than are consumed; while the high temperature reactor which is being designed for possible aircraft application puts the most severe temperature—and chemical—demands on its materials. Additionally, the interest in homogeneous reactor systems, if it bears fruit, would indeed reduce the word reactor practically to the meaning it has in ordinary chemical parlance—a big pot in which energy is generated by nuclear (rather than chemical) reaction.

To all intents and purposes, then, reactor technology has become a chemical technology, and as the program of reactor building at Arco, and the program at Oak Ridge indicate, it has become an experimental science. This experimentalization of reactor development appeals strongly to chemical engineers who, insofar as I know them, are inclined to be a rough and ready lot—who like to try things out—who are, if you like, inevitable optimists.

The fact that reactor technology has become both a chemical technology and an experimental technology, should I think, place strong pressures on physicists (who never were very practical, I suppose) to move over and to make more room for the chemical engineers—in fact should make them more inclined to hand to the chemical engineers the major burden of reactor development.

I presume there are theoretically two ways to proceed—one to teach the physicists chemical technology, the other to teach the chemical engineers nuclear physics. I am convinced the latter is proper—for reactor engineering is an engineering science; the physicists too often are unhappy, are vaguely dissatis-

ATLANTIC DEVELOPS NEW REFORMING PROCESS

A CATALYTIC reforming process which produces better quality gasoline in greater quantities, was announced recently by the Atlantic Refining Co., Philadelphia. According to Atlantic spokesmen, the success of the new process depends upon a new platinum catalyst-carrier combination, and the success of the process has been proved by the seven-months' operation of a pilot plant which processes more than 200 gal. of gasoline a day. More than 50,000 gal. of the new gasoline has been produced by this method.

Atlantic, which plans to lease the process to other petroleum refiners, is building at its Philadelphia refinery a large reformer unit which will have a capacity of 11,000 bbl. a day.

Another feature of the reforming process is that it will provide an important additional source of benzene, toluene, and xylene, should the supply of these products become critical. Benzene has been in short supply and it is an important ingredient in the production of synthetic rubber, nylon, plastics, etc.

Gasoline Process

The charge stock for the new catalytic process may consist of any fractions of crude naphtha up through normal gasoline, natural gasoline, and mildly thermally cracked naphthas. According to the company, the catalyst does not require special rerunning facilities preceding the reaction section and sulfur and normal water concentrations are not contaminants. A flow sheet for the process is shown in Figure 1.

Operating conditions in the catalytic reactors were said at the conference to be 950° F. and 500 lb./sq.in. pressure, with the ranges being between 850° to

TABLE 1

Component	Proportion Before Catalytic Reforming %	Proportion After Catalytic Reforming %
Aromatics	10	50
Naphthenes	40	4
Isoparaffins	25	28
Paraffins	25	18

1000° F. and pressures of 300-700 lb./sq.in.

As shown on the flow sheet, the charged naphtha is mixed with a recycled hydrogen stream and heated by exchange with reactants coming from the catalytic converters. A furnace brings the reactants to the proper temperature and the charge is passed through catalyst beds in series with reheaters between the reactors to compensate for endothermic reheater reaction. The effluent is cooled by exchange, as explained before, plus additional water cooling, and flows to a high-pressure gas separator. Here hydrogen of about 97.98% purity is withdrawn, compressed and returned to the reactors as recycle. Part of the hydrogen gas is used as fuel. The liquid from the separator is then passed through a fractionating tower for stabilization.

Catalyst

According to the company, the catalyst properties are balanced by operating conditions to yield an optimum combination of the desired isomerization and dehydrogenation reactions while cracking reactions are held at a minimum. This is borne out, it was said, by the high purity of the hydrogen recycle when operating at extreme conditions in reforming. If charge stocks containing kerosene are used regeneration may be required to remove quantities of coke.

Regeneration may be done while the catalyst is in place.

The new catalyst will be commercially manufactured by the Davison Chemical Corp. of Baltimore.

Production Results

An East Texas crude naphtha, a typical reformer stock, having an octane rating of about 55 without tetraethyl lead, was raised to 73.6, 79.8, and 85.0 octane number for each pass. For producing benzene the company also released figures for operation on a once-through C_6 straight fraction. The original charge contained 26.5% cyclopentanes, and 29.6% cyclohexane, 36.2% paraffins and 7.4% benzene. In the product after processing the cyclopentane and cyclohexanes were converted and the resulting content of the benzene went up to 45.8%. Cyclopentane was down to 6.8% and cyclohexane down to 0.8%. Paraffins were 32.7% and toluene 4.9%. C_3 and C_4 fractions made up the rest.

A similar result was obtained in the production of toluene from a once-through operation on a C_7 fraction from crude naphtha. A once-through conversion of about 95% of the cycloparaffins was achieved and actual figures are as follows: the charge stock contained, 35% paraffins, 26.2% cyclopentanes, 28.3% cyclohexanes, no benzene and 10.2% toluene. In the product there was 19% paraffin, 2.1% cyclopentanes, 0.8% cyclohexanes, 2.4% benzene and 26.6% toluene. Other aromatics, C_3 and C_4 accounted for the remainder. As is to be expected in a reforming process, the improvement in the raw gasoline is made by affecting the paraffin, isoparaffin, naphthene and aromatic components to give better octane products. The naphthenes are converted to aromatics by dehydrogenation and the paraffins are isomerized to produce isoparaffins.

The company released the information in Table 1 showing the change in raw gasoline through the new reforming process.

Economic Advantages

At the conference, H. W. Field, vice-president and general manager of the research and development department, and Merrill J. Fowle, director of the refining division, made out a strong case for the place that the new process will

Flow sheet of reforming process.

REACTORS STABILIZER

NAPHTHA AND RECYCLE GAS HEATER

REHEATER

NAPHTHA CHARGE

GAS TO FUEL

REBOILER

GAS TO RECOVERY

RECYCLE GAS COMPRESSOR

STABILIZED REFORMATE

ATLANTIC REFINING

have in the petroleum field. At present, the fuel will probably be used for either aviation gasoline or blended in with other gasolines for the present motors of today's cars. It is possible to get a 98 octane rating with the reformed material through the use of tetraethyl lead.

According to the company spokesman, the improvement in gasoline production is such that if the entire American oil industry used the process, 2,000,000 more motor cars would be able to operate from the same amount of crude. Under today's existing conditions, according to the company, with catalytic cracking and thermal reforming, a 92 octane number gasoline is possible with a 45% yield, whereas with the use of cracking and the new catalytic reforming process octane numbers of 98 are possible with 48.4% yields. Since the company figures that the economy factor is 18% better, a combination of the two processes will yield a 27% over-all better performance on the petroleum being used today.

Also, the company has its eye on the future motor car industry, and a demonstration with a test car, which had a compression ratio of 10:1, showed the new fuel to be satisfactory in its operation since it did not cause knocking. In addition, the company also pointed out that high octane aviation gasoline may become extremely important, and this process was able to produce it in large quantities. If a limited supply of lead reduces the supply of tetraethyl lead, the effect on gasoline quality will not be as great if the high octane gasoline fuel is available. If the new reforming process were used by the entire American oil industry, the company claimed, daily production of an additional 3,400,000 gal. is possible.

PENNSALT COMPLETES ALA. CHEM. PLANT

The Pennsylvania Salt Manufacturing Co.'s new plant for formulating insecticide concentrates and finished insecticide products at Montgomery, Ala., has been completed and is now in production.

The plant, Pennsalt's first in the Southeast, also includes a new district sales office of the agricultural chemicals department to serve southeastern agriculture. J. Drake Watson is district sales manager and R. O. White is plant superintendent.

FELLOWSHIPS CONTINUED BY PAN AM. REFINING

Pan American Refining Corp. recently announced that its previous policy of

"In recognition of his initiating and establishing the first college course of pulp and paper technology in the country at the University of Maine," the University of Maine Pulp and Paper Foundation presented R. H. McKee, consulting chemical engineer of New York, its 1951 Honor Award. The award, first of its kind made by the Foundation, was presented at the annual meeting of the University of Maine Pulp and Paper Alumni at a luncheon at the Biltmore Hotel, N. Y., Feb. 23. This Foundation, launched just a year ago is designed to provide financial assistance to undergraduates taking the five-year program in operational management in the pulp and paper field. Mr. McKee is shown above accepting the award from J. L. Ober, vice-president of Scott Paper Co., Chester, Pa., who was recently named chairman of the executive committee of the Foundation. Dr. McKee's career has covered industrial and teaching assignments. His teaching career included posts at Wooster, Carthage, Lake Forest and Maine. He was professor of chemistry and chemical engineering at the University of Maine from 1909-16 and professor at Columbia University from 1918-39.

granting study fellowships was to be continued during the academic year 1951-52. Pan American's primary purpose in granting these fellowships is to provide funds for basic research in the general fields of chemistry and chemical engineering.

Fellowships in chemical engineering are being continued at the University of Illinois, Massachusetts Institute of Technology and Rice Institute, the company stated.

SAFETY STANDARDS ASKED

Groups concerned with the manufacture, distribution, and use of anhydrous ammonia and ammonia solutions recently recommended that the American Standards Association organize a committee to develop safety standards. At a conference, these groups proposed that the work cover design, construction, location, installation, and operation of anhydrous ammonia systems as well as transportation and storage of anhydrous ammonia and ammonia solutions. Ammonia manufacturing plants, refrigerating, and air conditioning systems would not be included.

Problems of handling and storing anhydrous ammonia have assumed nationwide importance because of the increasingly widespread use of this gas as a soil fertilizer. Since anhydrous ammonia is usually transported in liquid form under pressure in tanks or cylinders, the relation between the strength of the tank and the pressure and temperature under which the gas is handled will be one of the problems to be given careful consideration.

The need for this work was called to the attention of the A.S.A. by the Compressed Gas Association which has offered its standards for the storage and handling of anhydrous ammonia and ammonia solutions for the committee's use. The conference recommended that the Compressed Gas Association be asked to sponsor this work.

The recommendations of the conference will be referred to the Safety Code Correlating Committee of the A.S.A. for final decision as to whether a committee will be set up under A.S.A. procedure.

Groups represented at the conference included the American Institute of Chemical Engineers,

F. J. CURTIS WILL RECEIVE C.C.D.A. HONOR

Francis J. Curtis, Past President of the American Institute of Chemical Engineers (1949), has been selected to receive the Honor Award for 1951 of the Commercial Chemical Development Association. Mr. Curtis will receive the award scroll at the annual meeting banquet to be held at the Roosevelt Hotel in New York March 21. The subject of the recipient's address will be "The Making of a Manager."

Currently vice-president of Monsanto Chemical Co., and director of industrial preparedness for the company in Washington, D. C., Mr. Curtis, a Harvard graduate, was affiliated with the Merrimac Chemical Co., from 1915-30. From 1935-39 he was assistant director of development, Monsanto Chemical Co. and subsequently became development director, and vice-president in 1943. Mr. Curtis has been active in the affairs of the A.I.Ch.E. and has served on many committees and as Director.

The C.C.D.A. award was established by the Association to provide annual recognition of an individual who has made outstanding contributions to the commercial chemical development field.

The general subject of the meeting will be "The Effect of Government Regulations on Commercial Chemical Development." The primary objective of the meeting is to effect a better understanding of both industry's and government's position in this matter. Representatives of government and industry are scheduled to speak.

GOODRICH FORMS JAPANESE SUBSIDIARY

Arrangements have been concluded between several large Japanese industrial firms and B. F. Goodrich Chemical Co. for a newly formed company, Japanese Geon Co., Ltd., to construct facilities in Japan for the manufacture of Geon polyvinyl chloride, it was announced by W. S. Richardson, president.

Mr. Richardson said that formation of the new company had been approved by the Japanese Foreign Investment Commission and the Supreme Commander of the Allied Powers General Douglas MacArthur, and construction would begin soon. Engineering design of the new plant, and manufacturing techniques, will be furnished by B. F. Goodrich Chemical Co., he added.

Principal stockholders in addition to B. F. Goodrich are three important Japanese corporations—The Furukawa Electric Co., Ltd., Nippon Light Metal Co., Ltd., and The Yokahama Rubber Co., Ltd., all of Tokyo.

F. J. CURTIS

The new polyvinyl chloride plant, located at Kambara, approximately 65 miles from Tokyo on Suruga Bay, will be staffed completely by Japanese.

Engineers of B. F. Goodrich Chemical Co. are to leave shortly for Tokyo to direct construction and initial operation.

COLLYER WANTS MORE RUBBER CAPACITY

John L. Collyer, president of The B. F. Goodrich Co., and former special director of rubber programs for the government, has urged that the government authorize immediately the building of plants to add 200,000 tons per year to the supply of general purpose American rubber.

Mr. Collyer said that this action is needed to deal promptly with situations created by the National Defense Mobilization Program and pressures which are needlessly costing the American people tens of millions of dollars a year.

He said that his recommendation was based on the following facts:

1. By vote of Congress, the government has retained a monopoly in the production of American rubber. It is carrying the full responsibility for providing supplies which are adequate to meet the needs and protect the interests of the American people.
2. As a part of the mobilization program, government is engaged in accumulating crude rubber for stockpiling purposes.
3. Buying for the stockpile is a serious problem now because of unusual purchases of natural rubber being made by other nations, including Russia and Communist China.
4. Our military plans are presumed to be based on the premise that in the event of war with Russia little or no crude rubber which is needed for the manufacture of large truck and bus tires would reach our shores. In such an event, moreover, the United States would be called upon to supply enormous quantities of rubber and rubber products to our Allies.
5. The only apparent reason for increasing further the government stockpile of crude rubber is this desire to be assured of adequate supplies at some time in the future. The stockpile already is adequate to supply the military and essential civilian

needs of the United States alone for a 5-year war.
6. Current demand for crude rubber—reflecting consumption and stockpiling needs and active speculation—exceeds the available supply. This is proven by the fact that crude rubber is selling at 70 cents a pound compared to 20 cents at the beginning of 1950.
7. This increase of 350 per cent in price means that the American people are paying tens of millions of dollars more a year for rubber products than is justified.
8. Increase of 200,000 tons capacity for the production of American rubber, authorized immediately by the government, would relax the necessity for large-scale purchases of additional crude rubber for stockpiling, at inflated prices.

Mr. Collyer pointed out that the world supply of crude rubber and American rubber in 1951 may reach 2,500,000 tons unless there is interference with the productions and shipment of crude rubber from the Far East. Normally this should be adequate to meet world consumption needs, he said.

Present capacity for the production of American rubber is 925,000 tons, and Mr. Collyer said that output is now at the rate of 700,000 tons, with capacity operation expected to be achieved by April.

CAUSTIC SODA PLANT FOR MATHIESON

Mathieson Alabama Chemical Corp., a new, wholly owned subsidiary of Mathieson Chemical Corp., will build a chlorine and caustic soda plant near Mobile, Ala., according to an announcement made by Thomas S. Nichols, president of both organizations.

Engineering has been completed for the new plant which will be located on a 500- to 1000-acre site at McIntosh, in the southern part of Washington County, approximately 40 miles north of Mobile. The new company plans to utilize salt from the McIntosh Salt Dome to supply salt brine, a necessary raw material for the manufacture of chlorine and caustic soda. Expected to be in operation by early 1952, the new plant will use the Mathieson stationary mercury cell process.

The new corporation's plant will be built by the chemical plants division of Blaw-Knox Construction Co., Pittsburgh, Pa. Electricity will be supplied by the Alabama Power Co.

Mathieson officials estimate that the plant will require approximately 100 employees when in full operation.

Officers of the new corporation are Thomas S. Nichols, president; John C. Leppart, executive vice-president; C. F. Prutton, vice-president; Stanley de J. Osborne, treasurer; J. V. Joyce, comptroller, and R. I. Galland, secretary.

A new boiler installation of the National Tube Co. at McKeesport, Pa., is using gas-wasting and electrostatic precipitation of combustion products in an effort to reduce atmospheric contamination. Designed to produce a minimum of fume and solids in waste gases, the new boilers are fired with gas from this U. S. Steel plant's four blast furnaces, with pulverized coal as an auxiliary fuel.

An average of 17,400,000 cu.ft. of gas/hr. is produced by the four blast furnaces. Of this amount, approximately 69%, or 12,000,000 cu.ft. is available for use in the new boiler house. Gas cleaning is accomplished in two gas washers and two electrostatic precipitators. A main 9 ft. in diameter conducts the gas from the furnaces to the washers. Based on a capacity of 230,000 cu.ft. of gas/min., the washers reduce the dust content to 0.25 gr./cu.ft. by passing the gas through multiple fine sprays of water. From the washers the gas passes to two double-compartment precipitators which reduce the dust content of the gas to 0.01 gr./cu.ft.

The dust in the precipitators is washed away constantly and flows by gravity to a 90-ft. diameter multiple-trough thickener. The sludge effluent from the wet washers is pumped to this same thickener. The settled solids from the thickener are pumped directly to a drum-type vacuum filter which can produce 172 tons of filter cake in 24 hr. This cake, with a moisture content of 25%, is scraped from the drum and dropped directly into cars for removal to the ore stock pile for recovery by sintering.

Gases and fly ash emanating from coal are controlled by dust collectors designed to meet the requirements of the new Allegheny County (Pittsburgh and environs) Smoke Control Ordinance. The ash-handling system is of the conventional-vacuum-type with a capacity of 20 tons/hr. It collects from ash hoppers, boiler soot hoppers, dust-collector hoppers, and stack hoppers, and delivers into a 100-ton capacity silo through a cyclone and air washer. Ashes from the silo are discharged into either trucks or cars by a dustless unloader.

CONFERENCE SCHEDULED ON RADIOISOTOPES

Radioisotopes in industry will be the subject fo a five-day conference to be held on the Case Institute of Technology campus in Cleveland, Ohio, April 2-6, presented in cooperation with the Atomic Energy Commission.

The purpose of the conference, which is the first of its type for industry, is to encourage a safe and wider industrial use of radioisotopes, according to John R. Bradford of the Radioisotopes Laboratory at Case, director of the program.

Faculty members of Case's departments of physics and of chemistry and chemical engineering will be supplemented by 11 visiting lecturers in the presentation of the program. Dr. T. Keith Glennan, member of the Atomic Energy Commission and president of Case on leave of absence, will address the dinner meeting of the conference April 5 discussing the Atomic Energy Commission and Industry.

The conference fee of $50 includes the ten regular sessions of the conference and tickets to the dinner and five luncheons. Copies of the program and registration forms may be obtained by writing to John R. Bradford, Radioisotopes Laboratory, Case Institute of Technology, Cleveland 6, Ohio.

The detailed program follows:

April 2—*Introduction to Nuclear Theory*—Robert S. Shankland, head, department of physics, Case Institute; *Nuclear Reactions*—John R. Bradford, Case Institute; *Atomic Energy—Uses and Benefits*—N. H. Woodruff, isotopes division, Atomic Energy Commission, Oak Ridge, Tenn.

April 3—*Radioisotope Production and Separation*—A. F. Rupp, superintendent, radioisotope development department, Oak Ridge National Laboratory; *Measurement and Characterization of Radiation*—Erwin F. Shrader, professor department of physics, Case Institute; *Interaction of Radiation with Matter*—Earl C. Gregg, Jr., professor, department of physics, Case Institute; *Biological Effects of Radiation*—H. L. Friedell, M.D., director, department of radiology, Lakeside Hospital, Western Reserve University.

April 4 — *Radiation Protection* — Otto Glasser, M.D., head, department of biophysics, Cleveland Clinic Foundation; *Medical Uses of Radioisotopes*—H. L. Friedell, M.D.; *Radioisotopes in Physical and Chemical Research*—G. D. Calkins, research engineer, Battelle Memorial Institute, Columbus, Ohio; *Planning a Tracer Experiment*—Rex Fluhardy, Oak Ridge Institute of Nuclear Studies.

April 5—*Pitfalls of a Tracer Experiment*—Rex Fluhardy; *Radioisotopes in Industry*—Charles Rosenblum, head, radioisotope laboratory, Merck & Co., Rahway, N. J.; *Typical Radiochemical Laboratories*—Tom B. Lanahan, S. Blickman, Inc., Weehawken, N. J.; *Instrument Problems of the Radiochemical Laboratory*—V. L. Parsegian, director, division of technical advisers, New York Operations Office, Atomic Energy Commission; Dinner Meeting, *The Atomic Energy Commission and Industry*—T. Keith Glennan, commissioner, Atomic Energy Commission, and president, on leave of absence, Case Institute of Technology.

April 6—*Decontamination and Waste Disposal*—C. C. Ruchhoft, chief, physics and chemistry section, research and development branch, Environmental Health Center, U. S. Public Health Service, Cincinnati, Ohio; *Industrial and Safety Problems Associated with Radioisotopes*—Rule Stratton, chemical engineer, The Travelers Insurance Co., Hartford, Conn.; *The Isotope Distribution Program*—N. H. Woodruff; Panel Discusion: general question and answer period.
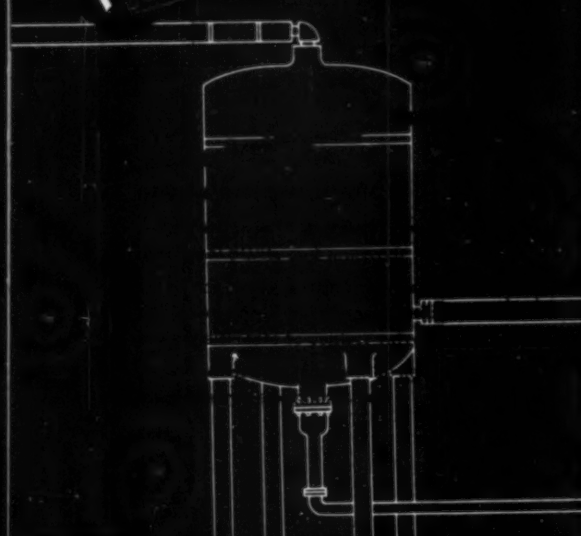
A.E.C. STATEMENT ON INDUSTRY PARTICIPATION

Following is the text of the recent statement by the Atomic Energy Commission on means of widening industrial participation in atomic energy development.

In recent months the Commission has received proposals from two industrial groups expressing willingness to bring their technical resources into the atomic energy program under somewhat different arrangements, in which a large share of initiative and responsibility would rest with the industrial group.
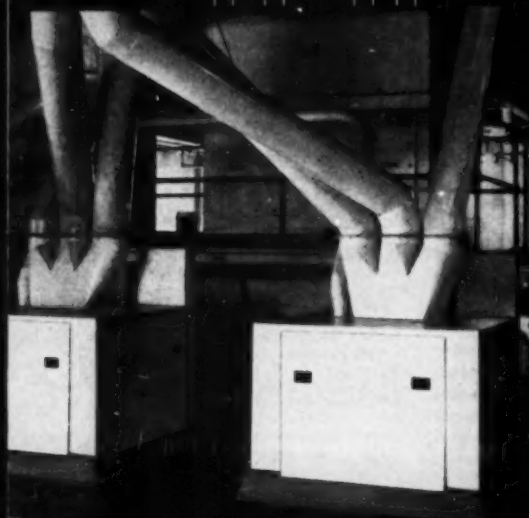
Both of these groups would study the feasibility of developing and operating nuclear reactors for the production of plutonium and with the ultimate goal of producing electric power. One proposal was presented by Mr. C. A. Thomas, executive vice-president of the Monsanto Chemical Company; the other by Mr. J. W. Parker of the Detroit Edison Company and Mr. M. E. Putnam of the Dow Chemical Company.

APPROACH TO
Distillery Operations

ONE of the more recent developments in a modern distillery is the *continuous* cooker. Grain, water and stillage flow to the cooker in automatically ratioed quantities . . . temperatures, pressures and levels are also precisely controlled . . . and the entire operation is synchronized by Brown Instruments located on a central panelboard.

This continuous cooker marks another step forward in the trend toward continuous processing in distillery operation.

When looking for recording and controlling instruments for your distilling operations, or for any *chemical process—consider first:*

* *The Brown know-how developed through many years of application experience in the industry.*

* *The completeness of the Brown modern approach —recorders, controllers, panelboards, valves, and all accessories.*

Write for Instrumentation, Vol. 5, No. 2, for description of an automatic grain feeding system.

Call in our local engineering representative for a detailed discussion of your process requirements . . . he is as near as your phone. Offices in more than 80 principal cities of the United States, Canada and throughout the world. MINNEAPOLIS-HONEYWELL REGULATOR Co., *Industrial Division*, 4427 Wayne Ave., Philadelphia 44, Pa.

MINNEAPOLIS
Honeywell
BROWN INSTRUMENTS

These proposals appear to offer not only
an opportunity for bringing new technical
and management resources into the atomic
energy program; they also are oriented to-
ward important Atomic Energy Commis-
sion objectives—the production of pluton-
ium and other important materials, together
with power, in a reactor; and they may
ultimately lead to arrangements where, be-
cause initiative is with industry, additional
incentives for rapid and aggressive technical
and business development will exist.

The Commission has discussed these pro-
posals with the men whose vision created
them, and has suggested conditions under
which it would be willing to go forward
with the first step involved in each proposal
—a study of its reactor development pro-
gram by qualified technical groups from the
industrial concerns involved. These groups
are visualized as consisting of ten to fifteen
individuals.

The following general policy guided con-
sideration of these proposals:

The Commission will undertake coopera-
tive activities with industrial concerns or
groups of concerns to explore possibilities
for their participation—on their own ini-
tiative, using their own resources—in devel-
opment of applications of atomic energy
for power purposes in such manner and
extent as to insure: (1) maximum atten-
tion to the atomic energy production pro-
gram in all its phases; (2) special effort
being placed on those matters that will be
productive in the relatively near future
(one to three years); (3) the application of
the best available brains to all the important
problems of the Commission.

To guide the general manager and staff
in considering further proposals in this field
from industrial concerns or groups, the
Commission has specified that those sub-
mitting such proposals should put forth a
well-defined set of objectives for their pro-
posed study, should be financially responsi-
ble and equipped with a staff of adequate
qualifications and size, and should under-
take to submit a report including detailed
findings and recommendations at the con-
clusion of the study. These reports would
be disseminated at the discretion of the
Commission to the extent consistent with
security.

The Commission has also directed that
no commitment be made at this time to
continue beyond the study phase. If satis-
factory arrangements can be made for pro-
ceeding with these studies, the Commission
will make available to properly qualified
and cleared persons existing information
and a reasonable share of the time of
Commission personnel.

Following closely on the A.E.C.'s an-
nouncement Monsanto Chemical Co. an-
nounced it was ready to go ahead with
a study of the feasibility of developing
and operating nuclear reactors for the
production of plutonium and with the
ultimate goal of producing electric
power.

The company made its position known
in a letter from Charles Allen Thomas,
executive vice-president, to H. D.
Smyth, acting chairman of the A.E.C.

In the letter to Dr. Smyth, Dr.
Thomas said Monsanto is ready to make

a study of basic data with the following objectives:

(a) Determine if sufficient materials and information exist to permit the design and construction of a nuclear reactor producing power and plutonium.

(b) Determine if such a reactor could make plutonium at a cost equal to or less than present costs and at the same time produce power at an economic cost, after application of credits for the plutonium produced.

(c) Recommend any additional research and development work required for the design of a power reactor.

(d) Set up the basic design premises for a power reactor producing plutonium.

Dr. Thomas stated that the cost of the study would be defrayed by Monsanto and any collaborators who might work with the company. He stated further that any such study would be based upon the understanding that the Commission would make available information pertaining to power reactors and that the Commission also would make available for reasonable consultation Commission personnel capable of contributing necessary data and experience. Dr. Thomas further stated that the conclusions determined by this preliminary work would be embodied in a report which Monsanto would submit to the Commission along with specific proposals for further actions to implement the completion of the project.

FIBRE V TO BE AMILAR

The Du Pont Co. has adopted the trade-mark Amilar for its synthetic polyester textile fiber which it has been evaluating since 1946 under the laboratory designation of Fiber V.
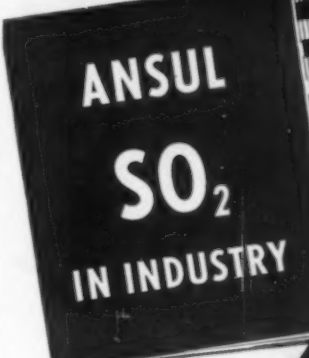
Technically, the material is a condensation polymer obtained from ethylene glycol and terephthalic acid. It is not chemically related to nylon, Orlon acrylic fiber, or any other Du Pont fiber.

Quantities of both continuous filament yarn and staple required for development work are being made in an experimental operation at the Seaford (Del.) plant of the nylon division.

Announcement was made late in 1950 of plans to use a 635-acre tract on the Neuse River, near Kinston, N. C., for the manufacture of Amilar polyester fiber. Design of the plant is under way and construction is expected to start sometime this year.

It has high tensile strength and high resistance to stretching—both wet and dry. It has good resistance to degradation by chemical bleaches and to abrasion. Most of the fiber's properties are equally good under wet or dry conditions.

CHEMSTRAND'S FIBERS PLANT AT DECATUR

The Chemstrand Corp. announced that Daniel Construction Company of Alabama, Inc., Birmingham, has been named general contractor to erect a plant for the production of synthetic fibers at Decatur, Ala.

The announcement was made by Osborne Bezanson, president of Chemstrand, a corporation which is jointly owned by Monsanto Chemical Co. and American Viscose Corp.

Mr. Bezanson said that construction will get underway immediately on a 656-acre site at Decatur. Manufacturing units, laboratories and general offices, as well as a powerhouse and other service facilities, will be erected at the location adjacent to the Tennessee River. The plant will employ approximately 500 persons.

Chemstrand acrylic fiber is currently being produced at a pilot plant at Marcus Hook, Pa. In its initial stage, the new synthetic fiber will be manufactured in staple form only.

ARMY WANTS ENGINEERS

Civilian position vacancies for more than 300 engineers and other technical personnel at the Army Engineer Research and Development Laboratories have been created by the stepped-up national defense program; Colonel O. B. Beasley, Commanding Officer of the Fort Belvoir Laboratories has announced. The positions, which are covered by Civil service regulations, carry salaries up to $6,400 a year.

An immediate need exists for mechanical, civil, electrical, electronic, chemical and photogrammetric engineers, technical writers, and architects.

LECTURE SERIES CHANGED

A change of speaker and date for the final lecture of the current series on Unit Operations, now being sponsored by the New Jersey Section of the A.I.Ch.E. was announced recently by D. S. Bruce, chairman of the Lecture Series Committee. The lecture on Drying Operations, originally scheduled for April 3, and to be given by S. J. Friedman will now be given April 5 by Prof. W. R. Marshall, Jr., of the University of Wisconsin. The meeting place remains the same, Newark College of Engineering.

According to the committee, 284 chemical engineers from the New Jersey area are taking the course of five lectures.

E.C.P.D. ANNUAL REPORT

Engineers' Council for Professional Development recently issued its 18th Annual Report covering 1950. This year the report featured an article on the function of E.C.P.D. entitled, "What Is E.C.P.D.?" As always, the booklet contains the report of the Committee on Engineering Schools which has examined and accredited 656 engineering curricula and 152 engineering schools. Copies may be obtained for 50 cents from the Engineers' Council for Professional Development, 29-33 West 39th St., New York.

ETHYLENE UNIT FOR GULF OIL CORP.

The world's largest single unit for manufacturing ethylene will be built at Port Arthur, Tex., by Gulf Oil Corp., an announcement of the company stated last month. Gulf also recently announced plans to manufacture iso-octyl alcohol, which marked its entry into the field of petrochemistry.

The new facilities will produce nearly 2½ billion cubic feet yearly, increasing total United States production by approximately 12 per cent. Included in the project will be an 8-in. pipe line 76 miles long, and a 6-in. pipe line of 32 miles to transport the gas to Gulf coast chemical plants.

The ethylene will be made from by-product gases produced in the refining processes at Gulf's Port Arthur refinery. These gases are at present used principally as fuel for the plant.

Construction will begin within two months and is scheduled for completion within a year after breaking ground. Building contract has been let to The Lummus Co., New York.

MARGINAL NOTES

Equilibrium Data in Orderly and Logical Arrangement

Distillation Equilibrium Data. Ju Chin Chu and Associates. Reinhold Publishing Corp., New York (1950) 296 pp. $6.00.

Reviewed by Wayne C. Edmister, Carnegie Institute of Technology, Pittsburgh, Pa.

A MUCH-NEEDED compilation of vapor-liquid equilibrium data is presented in this book. Experimental data from 107 references are presented in tabulations with mole percentages of each component in both phases, temperature in degrees centigrade and pressures in millimeters of mercury. The order is alphabetical for the common name of the most volatile component.

Data on 145 binary systems are given on 228 pages. Data on 27 ternary systems fill 54 pages, while the data on four multicomponent systems occupy six pages. The organization of the data is convenient and logical. The data are not smoothed or presented in even values of mole %, temperature or pressure by interpolation. Although this might insure precision, which is the reason the authors give for not doing it, the utility of the original data is not much improved.

The value of such a volume of data depends upon its completeness. The authors state in the preface that an attempt was made to collect these data exhaustively. In going through the book, this reviewer noticed two omissions. Kay published data on the binary systems ethane-heptane, butane-heptane and ethane-butane. Only the latter data were included in this book. Gilliland and Scheeline published data on propane-isobutane, propane-hydrogen sulfide and propane-isobutylene. Only the latter data were included in this book.

Since these two binary investigations cover related systems, it is unfortunate that some data were omitted. However, this may not be typical of the degree of completeness of this compilation.

The fact that the book is not complete in the hydrocarbon field detracts from its value as a research tool, while the fact that the data are not tabulated at even values of composition, temperature and pressure detracts from its value as a design tool.

However, this book is a worthy advance in its field. The authors are to be commended on the contribution. The book is recommended to chemical engineers having vapor-liquid equilibrium problems.

Statistical Engineering in the Chemical Process Industries. James R. Thomen Chemonomics, Inc., New York. Lithoprint, paper bound. (1951) 48 pp. $2.00.

THIS pamphlet is a collection of abstracts of articles discussing and describing the application of statistical engineering methods in the process industries. The abstracted articles deal with quality control, design of experiments, determination of specifications, analytical determinations, etc., and cover such phases of the chemical process industries as pulp and paper, petroleum, plastics, organic chemicals, etc.

Chemical Operations From Military Experiments

Methods of Operations Research. Philip M. Morse and George E. Kimball. First Edition Revised. Published jointly by The Technology Press, Massachusetts Institute of Technology, and John Wiley & Sons, Inc., New York. (1951) viii + 158 pages. $4.00.

Reviewed by D. H. Killeffer, Chemical Consultant, New York.

O PERATIONS research" as the term is used here has nothing to do—except incidentally as it does with innumerable other categories of phenomena—with the unit operations of chemical engineering or with the matter of operating plants. Rather the term is applied to a highly valuable extension of the methods of statistical analysis into the useful projection of statistics into the future as a basis for executive decision. The book begins with a terse definition: "Operations research is a scientific method of providing executive departments with a quantitative basis for decisions regarding operations under their control."

The techniques described are those which proved invaluable in evaluating and reconciling data to form the bases of vital decisions by the commanders in World War II. Although the methods here described are primarily illustrated by examples drawn from military activities, their application to many of the problems of chemical engineering and of chemical operations generally can be readily made by the qualified reader. Basically the methods and techniques described are familiar statistical tools, but their extension and refinement under the compulsions of war have given them new value and usefulness for application to other problems. It is a valuable book that should be familiar to all concerned with the problem of providing bases for executive decisions, or of making such decisions themselves.

Chemical Facts & Figures. Manufacturing Chemists' Association, Inc., 246 Woodward Building, Washington 5, D. C. Third Edition (1950) 429 pp. $3.00.

A NEW third volume of Chemical Facts & Figures is off the press and though it is only a few pages longer than the second edition, which was issued in 1946, it seems to contain much more information. We cannot detail all the information that the volume holds, but a fair statement would be that it contains almost every publishable business statistic available on the chemical field.

It contains indexes of production as well as actual production by value and tonnage. It includes summaries and tables of interest to the statistician as well as the executive. For instance, there are tables on the status of the synthetic rubber plants as well as capacities, plant investments, etc., plus a table showing the present owners of all synthetic rubber plants sold by the Government.

The volume includes tables of average hourly earnings in the various branches of the chemical field and allied industries, working hours, number of wage earners, index of factory pay rolls, and an extensive table on the financial records of 100 chemical process companies, imports, exports, etc.

This particular volume covers 1946 through 1949 and contains partial data on the first six months of 1950.

Canadian statistics and data on 500 new chemicals which have become available since the last edition are new additions.

For those concerned with the markets, sales, economics and trends of the chemical industry, this volume becomes a must for their libraries.

MARGINAL NOTES

Much Ado—About U & Pu

Sourcebook on Atomic Energy. Samuel Glasstone. D. Van Nostrand Co., Inc., New York. (1950) 546 pp. $2.90.

Applied Nuclear Physics. Ernest Pollard and William L. Davidson. Second Edition. John Wiley & Sons, Inc., New York. (1951) 341 pp. $5.00.

Toxicology of Uranium. National Nuclear Energy Series. Dr. Albert Tannenbaum, Editor. McGraw-Hill Book Co., Inc., New York (1951) 333 pp. $3.00.

Analytical Chemistry of the Manhattan Project. National Nuclear Energy Series. Clement J. Rodden, Editor in Chief. McGraw-Hill Book Co., Inc., New York. (1950) 748 pp. $6.75.

THERE is one pile in the nuclear field that American enterprise has already built—for profit—with the full cooperation of the Government. The pile grows larger every day in the libraries and in the corners of the book reviewer's office—the huge pile of books on Atomic Energy, Atomic Physics, Atomic War, Atomic Survival, ad infinitum. Yet, among the welter of books that are being published, many authoritative works are beginning to find their way out of the laboratories, plants and libraries of the Atomic Energy Commission.

One of the sturdy building blocks in the atomic energy literature is a new offering—a source book on atomic energy by Samuel Glasstone, published by D. Van Nostrand Co. Inc. This was written and published through a combined effort of the Atomic Energy Commission and the publishers. The project was begun early in 1948 as a means of preparing a source book on atomic energy for the use of authors, editors, classrooms, etc. Dr. Glasstone is already known for his book in collaboration with Hugh Taylor, on physical chemistry, as well as his own book on theoretical chemistry published in 1944. He is now a consultant to the Atomic Energy Commission.

The book is well written and undoubtedly answers a deep-felt need for an authoritative discourse on the atomic field. One of the most pleasing features of the book is its typography. On a 9-in. by 6-in. page, the publishers have run the text in two columns. The text is large enough and spaced well enough so that reading is simple and rapid.

The 18-chapter book is well interspersed with subdivisions of chapters and center heads which break up the individual subchapters into smaller sections with each paragraph numbered.

The trend to the smaller type line is gratifying and could well be followed by publishers of other textbooks.

As for the content of the book, its authoritarian source cannot be questioned, since Dr. Glasstone studied the work of various laboratories of the Atomic Energy Commission and the manuscript was reviewed by many scientists associated with the program. It has passed the censor and has enlisted the help of a great number of people competent in the field. Technically, the book begins with the earliest concepts of the atom building up through the molecular theory, periodic system, constituents of the atom, etc. Energy and radiation, the structure of the atom, chapters on radioactivity, its measurement, isotopes, the neutron, nuclear fission, utilization of nuclear energy, the new elements, the uses of isotopes, cosmic rays and mesons. This is merely a partial listing of the chapters but gives some indication as to detail and scope of this book. Each chapter is remarkably complete with much information collected from various sources. For instance, the chapter on the use of isotopes covers the labeling, use of isotopes for biological work, a discussion of the curie and considerable detail on the synthesis of labeled compounds. Isotopic tracer methods and application of isotopic tracers are even more fully discussed, with a short section on industrial applications.

The above remarks are made as an example of how complete Professor Glasstone has made the book, and certainly they, namely, the American Textbook Publishers Institute and Atomic Energy Commission have accomplished their objective of preparing a, "---comprehensive sourcebook of atomic energy for the use of textbook authors and editors." Not only are the Atomic Energy Commission and Professor Glasstone to be congratulated on this book, but also the publishers of the volume for the clarity and straightforwardness of the presentation.

The second book in this review of atomic literature is on applied nuclear physics by Pollard and Davidson.

This is a second edition of a book which first appeared in 1942. The authors are a professor of physics at Yale University, and a director of physical research for the B. F. Goodrich Co.

As is pointed out in the preface, much has happened since the first edition, and the work begins with the concept of the atom, and is entitled, "Randomness, Reason, and Atomic Energy." The book, however, approaches the problems strictly from the physics standpoint and much of the book is concerned with transmutation, nuclear fission, nuclear chain reactions, etc. The book is well

founded and authoritatively written. The chapter on the detection of nuclear particles, gives a good résumé of the various types of detectors, recording equipment, scaling circuits, counters, etc., used in atomic physics.

The first third of the book is a preparation for the latter two thirds, and has an excellent chapter on methods of accelerating atomic particles. The latter two thirds of the book deals with the transmutation of the elements, with a complete résumé, description, and explanation of the various reactions.

This is another first-class book.

The chapter on nuclear fission, while adequate is not as speculative as similar chapters in other books. This is commendable for the authors have withstood the temptation to expand beyond what they should. One rather interesting feature is the recitation of facts on fission that were common knowledge before World War II. Numerous pages have been devoted to developing that knowledge up through the first Chicago pile, through the Clinton and Hanford piles, and piles moderated with heavy water. The development of the portion of the chapter on power piles is well done and restrained.

The appendix to this book is rather interesting, too. It lists dates of important developments in the nuclear field; gives an extensive table of atomic species according to the atomic number, the abundance or half-life, particle energies and the quantum energies. This is the first time to this reviewer's knowledge that such a table has been run in a text of this sort. It is not complete, as is explained, but nevertheless, it is extremely useful.

Two recent volumes of the now famous Nuclear Energy Series, are next in our review, and while probably of not too great importance to chemical engineers in general, the information is important to anyone working in the nuclear field.

The first is on the "Toxicology of Uranium," edited by Dr. Albert Tannenbaum, director of cancer research of the Medical Research Institute of the Michael Reese Hospital, Chicago. The volume is part of the over-all plan on the plutonium project which is the fourth division of the projected eight divisions of the National Nuclear Energy series which, when completed, is expected to consist of 60 volumes. The book has many contributors and contains eight chapters plus sixteen collected papers, all devoted to the toxicological effects of uranium. As far as this reviewer can judge, it is a thoroughgoing authoritative book, well worth the investment which is really not prohibitive when considered in the light of the num-

CANDIDATES FOR MEMBERSHIP IN A. I. Ch. E.

The following is a list of candidates for the designated grades of membership in A.I.Ch.E. recommended for election by the Committee on Admissions.

These names are listed in accordance with Article III, Section 7, of the Constitution of A.I.Ch.E. which states:

Election to membership shall be by vote of the Council upon recommendation of the Committee on Admissions. The names of all applicants who have been approved as candidates by the Committee on Admissions, other than those of applicants for Student membership, shall be listed in an official publication of the Institute. If no objection is received in writing by the Secretary within thirty days after the mailing date of the publication, they may be declared elected by vote of Council. If an objection to the election of any candidate is received by the Secretary within the period specified, said objection shall be referred to the Committee on Admissions, which shall investigate the cause for such objection, holding all communications in confidence, and make recommendations to the Council regarding the candidate.

Objections to the election of any of these candidates from Active Members will receive careful consideration if received before *April 15, 1951*, at the Office of the Secretary, American Institute of Chemical Engineers, 120 East 41st St., New York 17, N. Y.

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CHEMICALS

1 • VINYL STABILIZERS. A technical report evaluating stabilizers for vinyl stocks by the Diamond Alkali Co. Reports all stabilizers commercially available. Contains description of standard formulations and all tests made. Results of the study are summarized in a table of recommended materials for use under severe exposures to heat and light.

2 • DIETHYL ACETYLSUCCINATE. A data booklet on diethyl acetylsuccinate fro mthe Monsanto Chemical Co. Gives the structural formula, physical data, chemical properties, reactions, syntheses, etc., for which the new material might be used. Suggested uses in addition to general organic synthesis; azo dyes and coumarin production.

3 • DICHLOROACETALDEHYDE. Research and development quantities of the chemical are offered by the Westvaco chemical division described in a new technical data sheet. Gives physical properties, suggested uses, etc.

4 • STARCH MODIFICATION. The use of peroxygen compounds to modify starches, proteins, and gums, is detailed in a 16-page data sheet of the Buffalo Electro-Chemical Co. End use of modified products is for gums, confectionery, sizing, adhesives, etc.

5 • WAXES. A collection of technical data sheets describing various waxes of the Concord Chemical Co. Description gives specifications, uses, packaging, formulations. Used as a substitute for carnauba and Japan wax.

6 • SILICONE ALKYD RESINS. Three new silicons alkyd coating resins, for single coat applications where heat, weather and chemical resistance, etc., are important, are announced by the Plaskon division of Libbey-Owens-Ford Glass Co. Bulletin describes

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properties, uses, resistances, etc., of these first chemically combined silicone alkyds.

7 • DRIERS. A new group of tallate driers for applications in paint as a replacement for naphthenates, is announced by Witco Chemical Co. Technical report of physical properties, etc., available.

8 • PLASTICIZERS. Pan American chemicals division has two new booklets on Panaflex BN. This is a high boiling synthetic hydrocarbon oil, and in booklet (8) its use is discussed as a coplasticizer for vinyl resins. Book gives physical properties of the compound, tells of its use

and advantages, giving physical data of resins made with these materials. Suggests uses. Booklet (8A) is on Panaflex BN for use with acrylonitrile rubber, where it also acts as a plasticizer. This follows the same general outline as the previous booklet and gives evaluations of use of the material on Buna N, Hycar, Paracril, etc. In every case, the characteristics of the rubbers are given in extensive tables.

9 • ORGANIC CHEMICALS. A new price list on more than 2400 organic chemicals from The Matheson Co. The list contains the company's regular line plus several hundred new compounds added recently. Alpha-

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1

betically listed, details of commodities, price, some physical data.

10 • TACKIFIER RESIN EMULSIONS. American Resinous Chemicals Corp. issued technical data sheets on tackifier resin emulsions for natural and neoprene rubber latices. The data sheets give the percent solids, pH, and other physical data of the corporations tackifiers. Gives compounding and handling information on making latex adhesives and describes how they are used in paper, plastics, shoe leather, etc., industries.

BULLETINS

15 • COOLING TOWERS. A well-illustrated booklet of the Hudson Engineering Corp. which describes its cooling towers, both natural and mechanical draft. Made of redwood. Illustrations of features, construction details, etc.

16 • DIAL THERMOMETER. A new dial thermometer by Palmer Thermometers, Inc. Mercury actuated, $4\frac{1}{2}$ in. dial. Features stem that can be placed at any angle and the dial face can be rotated to a readable position.

17 • FINTUBES. A new bulletin of the Brown Finture Co. on a new integral one-piece Fintube. Bulletin describes construction, gives range of sizes and materials, applications, etc. Materials are carbon steel, stainless, Inconel, Monel, aluminum, etc. Engineering data; comparison of square feet of bare pipe to Fintubes, heat transfer on finned side in heat exchange, friction factor chart, plus finside film correction graph.

18 • VALVE-SIZING CHARTS. A chart suitable for notebook by the Fischer & Porter Co. for sizing valves in steam use from 1 to 1,000,000 lbs./hr. Opposite side has a butterfly valve sizing chart covering a range of 15 to 10,000 gals./min.

19 • NOZZLES. Spray Engineering Co.'s complete catalog of spray nozzles for industrial purposes. A data sheet for each nozzle is given showing dimensions, lengths, gallon flow rate for varied pressures, spray patterns for various pressures, and other pertinent data.

20 • EQUIPMENT BULLETIN. A miniature product bulletin of the Sturtevant Mill Co., shows its equipment line. Small, easily handled, booklet covers crushing, grinding, separating, elevating, conveying, and mixing machines. In most instances the capacities, sizes, specifications, etc., are given.

21 • STEAM PLATEN PRESSES. Baldwin-Lima-Hamilton Corp. in a new 20-page bulletin shows the types of steam platen presses it manufactures. Presses range from 20 by 20 in. up to 84 by 222 in. and from 100 to 12,500-ton capacity. For use in various industries—rubber tile, plywood, linoleum, rubber goods, grinding wheels, etc.

22-23 • SPECTOGRAPHIC SERIES. Baird Associates, Inc., offers new technical literature on spectrographs. (22) Shows the source unit of the Board spectrograph and illustrates simply, the operation and meaning of the unit. (23) describes a 3-meter grating spectrograph and beside showing operation and functioning, it tells advantages, uses, etc.

24 • WATER AND LIQUID LEVEL GAUGES. The Bristol Co. with a new 24-page bulletin on water level gauges, describes instruments for measuring and recording water depth in tanks, tail races, lakes, reservoirs, etc. Describes float, pressure bulb, pressure, counterpoise, differential pressure and air-bubbler types of gauges. For all liquids and solutions, corrosive, flowing, viscous, etc. Completely illustrated plus engineering data.

25 • QUANTOMETER. A spectrometer and recording console made by the Applied Research Laboratories, which is designed as a low-price instrument suitable for rapid routine, direct-reading analysis. Covers the range between 2000A° and 8000A°. Records per cent concentration directly on paper. Slated for control analyses of metals and nonmetallics. Units are pictured and individual parts shown.

26 • AIR-COOLED HEAT EXCHANGERS. The Fluor Corp., Ltd., describes a new Fluor-GR fin-fan air-cooled heat exchanger. This equipment is designed to cool liquids or gases in capacities to meet air requirements at pressures up to 5000 lbs./sq. in., and temperatures up to

1500° F. Designed as a replacement for water-cooled exchangers, as a low maintenance method of cooling liquids and gases or condensing vapors. Bulletin shows construction details of each part, plus an exploded view of the complete structure. Installations are shown.

27 • OPERATING MODEL. A unique cardboard working model to demonstrate a new principle in Venturiball valves, is offered by the Paul Valve Corp. Demonstrates how the ball is directed by a guidepin into the seat.

28 • ALLOY CASTINGS. For the engineer that has abrasive, corrosive, or high operating temperatures that are destructive to normal metal life, the Stoody Co. offers a catalog on castings of hard metal alloys. Book is illustrated, describes the types of castings available, tells how to order them and pictorializes the various specimens turned out by the company.

29 • LIME HYDRATOR. Hardinge Co., Inc., offers an 8-page catalog on continuous lime hydrators. Flow sheet shows operation, engineering drawings, gives dimensions and capacities which vary from 1 ton/hr. to 45 tons/hr. Construction details of the hydrator are given.

30 • INSTALLING CENTRIFUGAL PUMPS. To help in the correct installation and operation of centrifugal pumps, Lawrence Machine and Pump Corp. is offering a bulletin which gives information on the problem. Tells about location, installation, correct piping, packing-box techniques, and common difficulties and interruptions.

31 • BUBBLE CAPS. A bulletin on standard alloy bubble caps made by The Pressed Steel Co. Gives designs of standard bubble caps plus dimensions, descriptions, slot areas, etc., of more than 150 different styles. Also on bubble-cap risers.

32 • DUST MANUAL. A 50-page book on industrial dust control through exhaust systems, by W. O. Vedder, is offered by the Pangborn Corp. The book gives complete detail on methods of controlling dust, covers exhaust systems, hoods and piping, dust-collecting equipment, operation and maintenance, etc. Covers air flow of various types of systems, gives information about filter cloths, settling chambers, etc. For the engineer with a dust-collection problem, this booklet should be of considerable help.

33 • POWER TRANSMISSION. An idea sheet from The Falk Corp. on how power transmission equipment can be used in the chemical process industries. Shows how motor reducers, couplings, speed reducers, and gears can be applied to such things as agitators, dust collectors, autoclaves, kettles, and other processing equipment.

34 • NUCLEAR SAFETY ITEMS. The Mine Safety Appliances Co. has just published a new eight-page booklet listing all the approved protective equipment of interest to industries directly concerned with atomic energy or nuclear studies. Photographs and details of 22 different safety items are included. Described in the booklet are respiratory protective equipment, air-sampling equipment, ventilation accessories, electrostatic samplers, etc.

EQUIPMENT

35 • FLOW REGULATING VALVES. For handling steam and water at high pressure drops, and especially flashing condensate, a new line of flow regulating valves is announced by The Swartwout Co. Uses projected include drainage for heaters, evaporator coils, process systems, feed pump recirculation, and others. Supplied in seven sizes ranging from 1 in. to 4 in. and standard 150 to 600 lbs./sq. in. Models that can stand pressures up to 2500 lbs./ sq. in. available.

36 • DENSITROL. A direct indicating instrument for measuring specific gravity has been added to the Precision Thermometer & Instrument Co. line of liquid density-measuring devices. Specifically designed to eliminate errors caused by liquid and gas interface in hydrometers, the device is totally submerged and can be used in continuous flow. Varied ranges of densities and viscosities. Available in varied materials of construction.

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37 • PRESSURE GENERATOR. The Milton Roy Co. for hydrostatic test purposes has developed a self-contained, fully automatic hydraulic pressure system for testing boilers, pressure vessels, piping systems, etc. Pressures up to 25,000 lbs./sq. in. can be developed from a 40 lb./sq. in. air pressure supply. Used also for pumping liquefied gases. It has full controls and completely portable units are available.

38 • VELOCITY CONTROLLER. A new proportional action velocity controller for controlling air velocities ranging from 50 to 250 ft./min., has been developed by Johnson Service Co. Primarily designed to control the velocity of air through doors of fume hoods in installations using radioactive materials, etc., the instrument works on the difference in pressure between two points. Extremely sensitive, regulator responds to pressure variations of .0001 in., water gage, and controls velocities within plus or minus 10 ft./min.

39 • SOLENOID VALVE. C. B. Hunt & Son, Inc., has just announced a new solenoid-operated single plunger valve. The valve is the usual Hunt valve, operates rapidly for high cycle requirement use. The valve value is furnished in a 2- 5-way design from ¾ in.-1 in. sizes. It will handle air to 200 lb./sq. in., and oil and water to 250 lb./sq. in. The solenoid moves a small pilot valve plunger which applies air to the operating piston to move the main valve plunger.

40 • HORIZONTAL PASTE MIXER. A 60-gal. stainless steel heavy-duty paster, with a stainless steel ribbon-type spiral agitator, is announced by L. O. Koven & Brother, Inc. Tank is jacketed for steam heating and agitator, driven by a 2-hp. gearhead motor, moves at 87 rev./min.

41 • TWISTITE BIN VALVE. A bin valve consisting of two sections of flexible rubber tubing, joined by a rotating collar, and which is closed by pulling on a cable wrapped around the collar, is new with the Stephens-Adamson Manufacturing Co. As the collar between the rubber sleeves rotates, the sleeves twist until they completely seal the opening. According to the manufacturers it is dust- and drip-tight, and is self-opening through the elasticity of the rubber sleeves which cause them to resume their cylindrical shape when the tension on the cable is released. The 6-in. valve is standard. Weighs 35 lbs. and will handle lump sizes up to 2½ in. Requires a 30-lb. cable pull for closure. Either local or remote control is possible by hand or motor operation.

42 • GAS-TIGHT DOORS. For chemical, food, products finishing, cleaning, etc., the Jamison Cold Storage Door Co. has an insulated door with a gas-tight vapor-tight seal. For use where gases, vapors, etc., must be contained within a certain area. Door has insulation against high temperature; has a heat-resistant gasket and adjustable sealing bars on all sides of the door.

43 • LEVEL DETECTOR. A displacement detector and transmitter for giving precise control of liquid levels and utilizing a bellows seal, is new with the Minneapolis-Honeywell Regulator Co. Uses a forced balance transmitter hooked up to a detector unit. A steel detector cage connected to the vessel in which the level is being measured, has a floating displacer which is connected through yokes and levers causing the pneumatic balancing bellows to be actuated. Air pressure is increased until it counterbalances the previous mo-

tion. When used in conjunction with a standard receiving controlling instrument, it controls and records liquid level. Full details available. Company indicates that one application will be in refinery fractionating towers to control rate of withdrawal of bottoms.

44 • FIRED HEATERS. Struthers Wells Corp. has a new standard line of direct-fired heaters with capacities from 100,000 to 15,000,000 B.t.u.'s/hr. Includes indirect circulating heating, using heat-transfer mediums such as Dowtherm. Bulletin available. Completely automatic in control.

45 • SOLVENT RESISTANT GLOVES. Plasticote Glove Co., Inc., offers a new plastic glove impervious to gasoline, and in addition, resistant to acids, hot oils, etc.

49 • SULFURIC FUME FAN. Development of an exhaust fan designed especially for handling sulfuric acid fumes, is announced by International Engineering, Inc. It is constructed of stainless steel capable of withstanding sulfuric attack up to 176° F. For use in chemical plants, steel mills, metal working shops, etc.

50 • STIRRER-PROPELLORS. For agitation in narrow-necked flasks, Fisher Scientific Co. has developed a 4-in. stirrer-propellor of 4 blades which can be opened up inside the flask to a larger diameter propellor. Called the Umbrella stirrer, it is equipped with a 12-in. shaft and will fit into any stirring motor accommodating ¼-in. rods. Made of stainless steel.

51 • SAFETY VALVE. An air-control solenoid valve introduced by Ross Operating Valve Co., is designed to give safety to operators. Even if air or electrical supply should be interrupted the valve will move to a safe position. Operates with line pressures of 40 to 125 lbs./sq. in. in ¼ in. to 1¼ in. pipe sizes. Valve incorporates all the features of the Ross valve.

52 • SPONGE RUBBER. A bulletin on sponge rubber from The Sponge Rubber Products Co. Gives the quality, grades and physical properties as well as test data on sponge rubber, influence of heat in aging, insulating value, etc. For industries using this product or contemplating its use, bulletin will provide much important data.

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Robert Thomas Bucsko, *Dayton, Ohio*

Walter T. Burchak, *Iselin, N. J.*

Robert V. Butz, *Texas City, Tex.*

Bruno P. Castiglioni, *Houston, Tex.*

Carlyle E. Cole, *Seattle, Wash.*

Grover C. Condon, Jr., *Baltimore, Md.*

Michael J. Connair, *Pennsgrove, N. J.*

Vernon A. Cornell, *Norwalk, Calif.*

Calvin E. Cox, Jr., *Midland, Mich.*

F. W. Crowe, Jr., *Pittsburgh, Pa.*

Robert Diekman, *Whiting, Ind.*

Eric A. Douglis, *Weehawken, N. J.*

Dallas Daniel Dupre, III, *Akron, Ohio*

Carl M. Edelblut, *University City, Mo.*

James A. Ellison, *Houston, Tex.*

John E. Ertel, *Pottstown, Pa.*

Donald Factor, *Barberton, Ohio*

Gerard W. Farnan, *Bellevue, Del.*

William V. Fello, *Baton Rouge, La.*

John H. Field, *Charleston, W. Va.*

James E. Friden, *Whiting, Ind.*

Leo Gans, *New York, N. Y.*

Fred Giordano, *Rosedale, N. Y.*

Albert J. Gnesin, *Whiting, Ind.*

Lawrence E. Greenwell, *Webster Grove, Mo.*

David Hacker, *Chicago, Ill.*

Henry E. Haley, *Houston, Tex.*

Howard F. Hand, *St. Louis, Mo.*

Sharad Hansoti, *Columbus, Ohio*

Paul D. Harthorne, *Aruba, N. W. I.*

Carl Hellman, *Wilmington, Del.*

E. Webb Henderson, *Phillips, Tex.*

Alfred M. Henke, *Springdale, Pa.*

James J. Higgins, *Rittman, Ohio*

Harry L. Hilleary, Jr., *St. Louis, Mo.*

Bernard L. Hoffman, *Rahway, N. J.*

Hal L. Hollister, *Richland, Wash.*

William H. Holmes, *Seattle, Wash.*

Robert D. Hornbeck, *Vancouver, Wash.*

Harold A. Houdek, *Fort Dix, N. J.*

G. M. Irving, *Riverbend, Quebec*

Anthony Morris Johnson, Jr., *Richmond, Va.*

William G. Johnson, *Grace, Idaho*

Harry A. Kahn, *Oak Hall Station, Pa.*

Richard W. Kersey, *Long Beach, Calif.*

Leon L. Kimball, *Provo, Utah*

John F. Kinney, *Atlanta, Ga.*

Erwin Maynard Koeritz, *Atlanta, Ga.*

Louis T. Lanz, *St. Louis, Mo.*

James A. Liontas, *Philadelphia, Pa.*

Milton Litvin, *Princeton, N. J.*

Charles B. Locke, *Beaumont, Tex.*

Thomas E. Louis, *Amherst, Va.*

Edward H. Lynch, *Gardena, Calif.*

Chester J. Malec, *Brooklyn, N. Y.*

M. C. Malone, *Edmonton, Alberta*

John Franklin McIntyre, *Liverpool, N. Y.*

A. Louis Medin, *Columbus, Ohio*

Roland L. Menzl, *Whiting, Ind.*

Carl F. Meyer, *Philadelphia, Pa.*

B. Misra, *New York, N. Y.*

Philip R. Monaghan, *New York, N. Y.*

Robert J. Moore, *Pittsburg, Calif.*

Frederick M. Muller, *Cincinnati, Ohio*

John S. Negra, *Iselin, N. J.*

Kenneth W. Nelson, *El Dorado, Ark.*

Herman Dail Nies, *Ostende, Belgium*

Edward J. Opatken, *Monessen, Pa.*

Vincent D. Patton, *Florence Villa, Fla.*

Morton T. Pawel, *Stamford, Conn.*

A. V. Peppard, *Pampa, Tex.*

John H. Pickin, *Newark, N. J.*

Robert G. Ragsdale, *So. Charleston, W. Va.*

Donald K. Reccius, *Louisville, Ky.*

Robert L. Reynolds, *Glendale, Calif.*

P. H. Richer, *Beaumont, Tex.*

Philip T. Riffe, *Parkersburg, W. Va.*

O. K. Roe, *Indianapolis, Ind.*

Henry J. Roux, *Lancaster, Pa.*

Fred E. Rowe, *College Park, Ga.*

Harry T. Schultz, *Brookline, Mass.*

Arnold G. Schwartz, *Newark, N. J.*

Philip A. Schweitzer, *Bound Brook, N. J.*

Junior DeVere Seader, *Madison, Wis.*

James Thad Shider, *Waynesboro, Pa.*

Warren C. Shultis, *Swarthmore, Pa.*

Tejinder Singh, *Kobuta, Pa.*

Jack H. Sloan, *Hanford, Calif.*

Dean A. Smith, *Harvey, Ill.*

Floyd M. Smith, *Akron, Ohio*

John Sosnowski, *Manchester, N. H.*

Richard E. Spangler, *Bound Brook, N. J.*

H. Kenneth Staffin, *Metuchen, N. J.*

Clarence Steelman, Jr., *Oil City, Pa.*

Paul E. Stein, *Cactus, Tex.*

B. E. Steinkuhler, *Springfield, Mass.*

Joseph G. Sueme, Jr., *Sappington, Mo.*

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P. Carroll Underwood, *Kingsport, Tenn.*

Albert L. VanAmburg, Jr., *Dayton, Ohio*

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John S. Wiederecht, *Somerville, N. J.*

Joseph W. Williams, Jr., *Miami, Fla.*

C. Oliver Wimbish, *Kingsport, Tenn.*

Irving Wolf, *Chicago, Ill.*

Walter E. Yedlinsky, *Woodbridge, N. J.*

Richard L. Yelton, *St. Albans, W. Va.*

CHEMICAL ENGINEER AND ATOMIC ENERGY

fied when they do engineering, while the engineers who like to do engineering will certainly learn physics as they have already learned chemistry.

When the chemical engineers have mastered mathematics and nuclear physics to the degree to which they have learned chemistry, there will emerge a new species of whom a few hardy individuals already are born—the nuclear engineer. The nuclear engineer will compute a critical mass on one day and compute a cost on the next. He will conceive a new reactor type and will guide the development of new materials for his reactor. He will do all this willingly because he likes to build things and make them work, and he will do it with understanding because he knows chemistry, mathematics, physics, and engineering. And on him—the nuclear engineer—will rest the future of atomic energy development.

An address presented before the Knox-ville-Oak Ridge Section of A.I.Ch.E., Oak Ridge, Tenn.

KANSAS CITY MEETING

and 10,000 separate serial titles, Linda Hall Library is a complete and convenient source of technical information. Midwest Research Institute was founded in 1944 as a nonprofit organization with the primary function of aiding in the industrial development of the Midwest region.

Kansas City and vicinity offer many extracurricular attractions to those attending this special meeting. In addition to numerous planned plant tours, there are available for both registrants and their wives, such facilities as the William Rockhill Nelson Art Gallery, Kansas City Museum and numerous points of historical interest. The Municipal Auditorium and its Music Hall present current plays, musical programs, and athletic events. The Country Club District is a world-renowned residential district whose beauty will be at its peak in May. Vacation areas of the Ozarks lie within easy driving distance to the south. Finally, as a special inducement for wives to accompany their husbands to the meeting, Kansas City is one of the outstanding centers of the nation for the manufacture of ladies' wearing apparel.

VIRUS KILLER MADE FROM ACETYLENE

At a press conference held last month, General Aniline and Film Corp. announced the development of a new substance which, based on tests to date, appears to be an effective and safe virus killer.

Called PVP-iodine by General Aniline, the substance combines iodine with polyvinylpyrrolidone.

The latter chemical has been in the news in the past few months because, based on its use by the Germans during World War II, it is known to be a superior substitute for blood plasma.

In combination with iodine, PVP acts as a detoxifier without destroying its high efficiency as a viruscide or germicide, according to Dr. Cary R. Wagner, General Aniline vice-president. "Physicians have known for many years," Dr. Wagner said, "that iodine possessed most of the qualities needed to combat a variety of germs and especially viruses, but its high toxicity when taken into the system prevented its use. Even its external applications have been reduced because it's a strong irritant and often results in severe burns. Our tests are not conclusive and more clinical study will be required, but the results so far have been most encouraging."

Polyvinylpyrrolidone is a product of actylene chemistry. Based on techniques originated by Dr. J. W. Reppe, an I. G. Farben chemist in Germany, General Aniline research men carried out high acetylene reactions in the company's central research laboratories in Easton, Pa., and in 1949 a new plant was opened at Grasselli, N. J., where acetylene derivatives, including *PVP* have since been made on a semi-commercial basis.

These facts were brought out at a recent conference at which Dr. Herman A. Shelanski, a General Aniline consultant, stated that his investigations prove that *PVP*-iodine is more effective than iodine alone in treating bacterial infections, is virtually nonirritating, toxicity greatly diminished and no sensitivity is produced. Dr. Wagner stated that research is continuing on an accelerated schedule.

PETROCARB EQUIPMENT, INC., ORGANIZED

Petrocarb Equipment, Inc., 30 Vesey Street, New York 7, N. Y., was recently incorporated under Delaware laws to specialize in high-temperature equipment and refractory constructions for the process industries including hydrocarbon and certain metallurgical operations.

At the initial meeting of the board of directors Arthur A. Turner was elected president; Kenneth W. Stookey and C. A. Stokes, vice-presidents, and Jo C. Calhoun, treasurer.

Mr. Stokes, a member of A.I.Ch.E., is director of research of Godfrey L. Cabot, Inc., Boston, Mass.

ALCOA EXPANDS ALUMINUM PLANT

Alumina production will be approximately doubled by March 15 at the East St. Louis works of Aluminum Ore Co., D. H. Tilson, works manager, said recently. Aluminum Ore Co. is a wholly owned subsidiary of Aluminum Company of America (ALCOA). An immediate increase of 50 per cent has put the plant halfway toward its mid-March goal. Mr. Tilson added. The East St. Louis plant-expansion program will cost more than $500,000.

COMPUTING MACHINERY MEETING IN DETROIT

A joint meeting of the Association for Computing Machinery and the Industrial Mathematics Society is scheduled for March 27 and 28 at Wayne University, Detroit, Mich. There will be papers on both analogue and digital machines and on their scientific, engineering, and business applications, together with a display of components.

MARGINAL NOTES

ber of pages, and the difficulty of obtaining such information, for anyone in the field.

Apparently all important information about the toxicological effects that is important, is included here and it is a report on investigations which began in 1942 under the auspices of the Manhattan Project.

The second volume is, "Analytical Chemistry of the Manhattan Project." Editor in Chief is Clement J. Rodden of the New Brunswick Laboratory of the U. S. Atomic Energy Commission. It has an impressive board of editors, and this volume is one of the series of Division VIII of the N.N.E.S. on the Manhattan Project.

This volume is divided into two parts, the first concerned with the determination of individual elements, and the second deals with general instrumental methods. It is well illustrated and does cover not only the uranium but also the determination of other elements in the presence of uranium and uranium salts.

The Condensed Chemical Dictionary. Fourth Edition. Francis M. Turner, Editorial Director. Revised and Enlarged by Professor and Mrs. Arthur Rose, State College, Pa. Reinhold Publishing Corp., New York, N. Y. (1950) 726 pp. $10.00.

A FOURTH edition of The Condensed Chemical Dictionary, which has been revised and enlarged by Professor and Mrs. Arthur Rose brings to the chemical industry an edition which lists 23,000 descriptions of industrial and other chemicals.

The new edition has 5000 new items and the section on chemical specialties, meaning those items sold under trade or brand names, has been expanded considerably.

The listings are alphabetical, and for the most part each chemical has detailed properties, grades, how shipped, uses, and the shipping regulations if any exist.

The original edition of this dictionary was issued in 1919 and this makes only the fourth revision since that time. The edition prior to this came out in 1942.

Books Received

The Polarographic Method of Analysis. Otto H. Müller. Chemical Education Publishing Co., Easton, Pa. No. 2 in Series of Contributions to Chemical Education. Second Edition, revised and augmented. (1951) 209 pp.

The Phase Rule and Heterogeneous Equilibrium. John E. Ricci. D. Van Nostrand Co., Inc., New York. 505 pp. $12.00.

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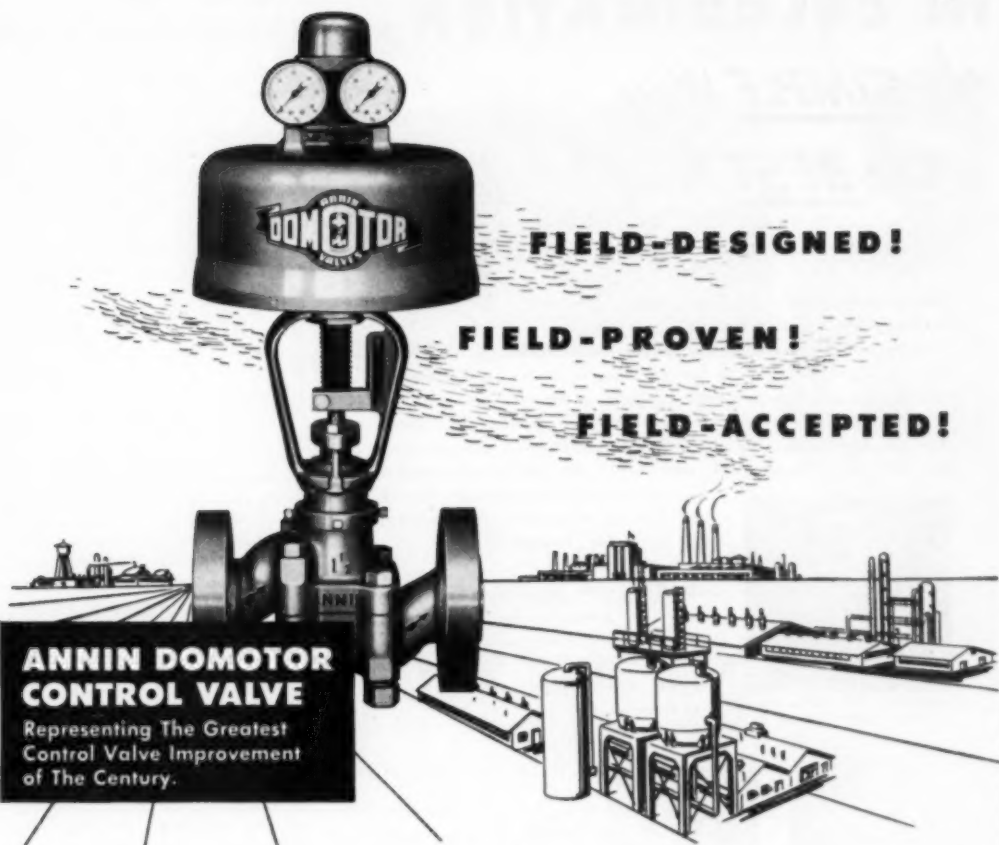
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ANNIN DOMOTOR VALVES

THE ANNIN COMPANY 3500 UNION PACIFIC AVE., LOS ANGELES 23, CALIF.

Engineers' Joint Council at a meeting late in January approved plans for a campaign to raise $100,000 from business and industry to publicize the function of engineers in today's industry.

Engineers' Joint Council Manpower Commission will use the funds solicited to accomplish three main objectives: (1) to overcome future shortages of engineering graduates by increasing enrollments in engineering schools, (2) to assure better utilization of present engineering manpower by alerting employers of engineers for better utilization caused by the impending shortage, and (3) to act as a consultant to government bodies in order to assist in the conservation of engineering manpower.

The commission has plans for expansion which call for an Executive Committee composed of a chairman and a commission member from each participating society, an editorial committee composed of seven members, and a development committee of six whose function will be to raise necessary funds.

E. G. Bailey is temporary chairman of the E.J.C. Commission which has placed itself at the disposal of the Scientific Manpower Advisory Committee of the National Security Resources Board.

1950 Report Issued

A major accomplishment of the year 1950 was completion of a survey of selected engineering personnel for the national military establishment. A contract was made between the Office of Naval Research and A.S.M.E. to conduct the survey under the general supervision of the E.J.C. Committee on Survey of Selected Engineering Personnel. Data were secured on 63,689 engineers of high standing, classified according to 253 specialties in which they are competent and ten major activities in the engineering field in which they are engaged. The records, forwarded to Washington, will probably be of value in the selection of key personnel by the military establishment and other agencies concerned with the security of the nation. Another activity of E.J.C. was embraced in the report of the Water Policy Panel, issued in June.

These and other accomplishments, notably the "Science Legislation Panel" which was instrumental in seeing that engineers were given proper representation on the National Science Foundation Board, give suggestions of definite progress heightened by detailed accounts of the various committee activities during 1950.

SECRETARY'S REPORT

S. L. TYLER

THE Executive Committee met at the office of the Secretary Feb. 9 with all members in attendance. The Minutes of the two previous meetings of the Executive Committee were approved and the Treasurer's Report for the month of January received and studied. Upon recommendation of the Committee on Admissions those applicants whose names were listed in the January issue of *Chemical Engineering Progress* were elected to the grades as indicated. In addition to the applicants whose names were printed, 555 Student members were elected bringing the total of Student members to 2,265. The following additions to committee personnel were approved: Local Sections—W. T. Read (National Capital); Membership—B. J. Duffy to replace H. H. Young; Program —G. Skaperdas.

R. S. McBride was appointed Institute representative to the American Documentation Institute with F. J. Van Antwerpen as alternate. Eight resignations were accepted. The name of Elbert E. Moore, a 1950 Junior member, was added to the Suspense List as he entered the Armed Services recently. J. G. Vail and C. M. A. Stine were appointed as Institute representatives to attend the Fifty-fifth Annual meeting of the American Academy of Political and Social Science to be held in Philadelphia, April 6 and 7. It was voted that a subscription to *Chemical Engineering Progress* be given to winners of the first and second prizes at regional student chapter conferences.

The Council of the Institute met on Feb. 9 at The Chemists' Club, New York. After approval of Minutes, J. H. Perry, chairman, Public Relations Committee, reported on activities of his committee especially on a proposed questionnaire to be sent to the membership. This matter was discussed thoroughly but no decisions were made and it will be made an item of business at future meetings of Council.

J. C. Elgin, chairman, Constitution and Bylaws Committee, attended the Council meeting to present a proposed draft of bylaws and to participate in discussion. It is hoped that a final draft of the bylaws will be presented to Council in the near future and that this will be approved.

Secretary presented letter from the Engineering Manpower Commission of Engineers' Joint Council requesting the underwriting on the part of this Institute of its share ($1,476) of an $18,000 estimated initial expenditure of the

GRADUATE EDUCATION IN CHEMICAL ENGINEERING

GEORGE GRANGER BROWN

Chairman, Chemical Engineering Education and Accrediting Committee, A.I.Ch.E.

FOR some years serious consideration has been given to the question of grading or accrediting schools for graduate instruction in engineering. The Education Committee has been charged by the A.I.Ch.E. Council to consider this matter and the Schools Committee of the Engineers' Council for Professional Development has a special subcommittee for this purpose. Before coming to any conclusion in this matter, the Chemical Engineering Education and Accrediting Committee of A.I.Ch.E. held an open forum on graduate education in chemical engineering at the annual meeting of the Institute at Columbus Dec. 3, 1950. This forum was attended by some four- or five-hundred men representing education and industrial activities. The discussion was opened by comments from: Prof. Alfred H. White, emeritus chairman, department of chemical engineering, University of Michigan and a Past President of the Institute; Dr. Thomas H. Chilton, technical director, engineering department, Du Pont Co., and President-elect; Prof. Walter G. Whitman, head, department of chemical engineering, Massachusetts Institute of Technology; Dr. Marvin C. Rogers, director of research, The R. R. Donnelly and Sons Co., Chicago. (For a summary of their remarks see Chemical Engineering Progress, Jan. 1951, p. 16, News Section.)

The discussion was focussed around the objectives of graduate instruction in chemical engineering and the minimum requirement that should be met for satisfactorily accomplishing these objectives. A large number of those present participated in the discussion of the points raised. As a result of the full discussion and a show of hands, the following statements were accepted unanimously by this group, except in the case where an exception is noted:

Objectives of Graduate Instruction in Chemical Engineering

1. To develop power in applying science to engineering problems.
2. To develop the student's ability to do creative work, to tackle new problems in design or research and arrive at an acceptable solution which should be presented as a report or as a thesis.
3. To provide more thorough grounding in the technology of chemical engi-

An important and hard-working committee of the A.I.Ch.E. is that on Chemical Engineering Education and Accrediting. It acts as a watchdog on standards and performance, and as a guide for schools that need help. Accrediting of chemical engineering curricula was begun by the Institute in 1925, some seven years before the Engineers' Council for Professional Development came into the field. Now it is faced with an important question—shall graduate programs be accredited also? Here George Granger Brown, former President of the A.I.Ch.E. and chairman of its Accrediting Committee and chairman of the department of chemical engineering at the University of Michigan, gives a complete résumé of developments up to now.

neering and fundamental sciences and become a master of some part of the broad field of chemical engineering.
4. To inspire the student to become an active leader and develop professional integrity.

Minimum Requirements of a Graduate Curriculum in Chemical Engineering

In order to accomplish the above it was considered necessary that the following conditions be met:

1. Admission of properly equipped individuals only.
2. The staff must be jealous of its standards and insist upon high standards of performance on the part of the students, including reading, writing, and speaking as evident in reports, examinations, recitations, and speeches, and skillful human relations as evident in their daily lives.
3. Members of the staff must themselves represent those qualities desired in the students.
4. Graduate program must include some research, design, or original project work wherein the student does creative technical work of his own.
5. An adequate number (at least two) members of the staff should be actively engaged in high quality creative work of professional caliber in addition to their teaching activities.
6. The Master's degree represents primarily graduate work conducted on a higher level than that required for the satisfactory completion of an under-

graduate program. (A small minority, less than 3% of those present, thought a Master's degree might represent the satisfactory completion of undergraduate work in fields or subjects other than those perused by the student as an undergraduate. This group thought a proper object of the Master's program was to "round out" the students in this manner). The statement as accepted does not preclude or eliminate advanced work in physics, mathematics, or other cognate subjects which may be required as senior courses of other students majoring in these fields as undergraduates, but such work of an undergraduate caliber should be a minimum and only that necessary for the student to continue these subjects at the graduate level.
7. Strong graduate programs in the physical sciences should also be available at the institution as basic support for the graduate program in chemical engineering.
8. The graduate program must not be rigid but should be designed to fit the requirements of the student. The success of the program is to be measured in terms of the end result and not by any particular grouping of courses.
9. The undergraduate curriculum should be fully accredited.
10. The over-all environment, facilities and teaching load should be such as to supply the inspirational environment required.

Two further thoughts have been submitted which should be considered in connection with the objectives of graduate education.

1. To develop in the student the habit of mentally screening each idea or problem for its major variables and their order of magnitude, thereby developing a basis for sound engineering judgment.
2. To stimulate the student to continue his studies through purposeful use of his leisure time throughout his life. It may not be feasible for him to find collaborators in technical studies, but there are few places where a group of individuals cannot be found who are glad to study social, literary, or other subjects of common interest. Such activities will make the individual a better citizen and fit him for wider responsibilities.

These matters are brought to your attention as indicating the current thinking and the area of the agreement regarding graduate education in chemical engineering.

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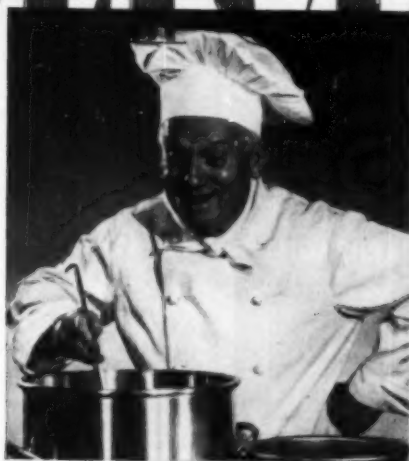
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LOCAL SECTION

OKLAHOMA

A meeting of this section was held Feb. 15, 1951, in the McKinley School Auditorium, Bartlesville, Okla. N. K. Anderson, director of the research and development department, Deep Rock Oil Corp., gave an address on "Problem of Research in a Small Organization." Dr. Anderson discussed the problems of research and development in a small company and stated that the small companies could profitably pursue small outlets of specialty products and utilize small quantities of by-products. The speaker emphasized that the future of research and development work in the smaller organization was in these small quantity special product markets and not in trying to compete with the large companies for the large volume markets.

The 1951 officers of this section are:

Chairman—H. I. Hays, Phillips Chemical Co.
Vice-Chairman—C. R. Ringham, Phillips Petroleum Co.
Secretary-Treasurer—D. H. White, Phillips Petroleum Co.
Executive Committee—F. H. Poettmann, Phillips Petroleum Co.; Virgil Scarth, Phillips Petroleum Co., and other officers listed.

Reported by H. W. Barber and D. H. White

PHILADELPHIA-WILMINGTON

The fourth meeting of the 1950-51 season was held at the Clubhouse Hotel, Chester, Pa., Feb. 13, 1951. The dinner was attended by 58 members and guests, and approximately 100 persons were present for the meeting that followed.

The speaker of the evening was Robert T. Sheen, president of the Milton Roy Co., who discussed "Automatic Control of Liquid Flow with Controlled Volume Pumps." Following the talk, Mr. Sheen showed some Kodachromes of the Texas City disaster and of an airplane trip over the Grand Canyon of Colorado.

Reported by W. E. Osborn

SOUTHERN CALIFORNIA

Officers of this section now serving are as follows:

Chairman—I. C. Bechtold, Fluor Corp., Ltd.
Vice-Chairman—F. J. Lockhart, University of Southern California
Secretary-Treasurer—G. R. Lake, Union Oil Company of California
Program Chairman—S. G. Sevougian, Dow Chemical Co.

Reported by Gale S. Peterson

FUTURE MEETINGS AND SYMPOSIA OF A.I.Ch.E.

Chairman of the A.I.Ch.E. Program Committee

Walter E. Lobo

The M. W. Kellogg Co.

225 Broadway, New York 7, N. Y.

MEETINGS

Kansas City, Mo., Hotel President, May 13-16. 1951.
Technical Program Chairman: Walter W. Deachner, J. F. Pritchard Co., Kansas City, Mo.

Rochester, N. Y., Sheraton Hotel, Sept. 16-19. 1951.
Technical Program Chairman: D. E. Pierce, General Aniline & Film Corp., 230 Park Ave., New York. N. Y.

Annual — Atlantic City, N. J., Chalfonte-Haddon Hall Hotel, Dec. 2-5, 1951.
Technical Program Chairman: Frank J. Smith, Pan American Petroleum & Transport Co., 122 East 42nd St., New York 17, N. Y.

Atlanta, Ga., Feb. 17-20, 1952.
Technical Program Chairman: H. E. O'Connell, Ethyl Corp., Box 341, Baton Rouge, La.

French Lick, Ind., French Lick Springs Hotel, May 11-14, 1952.
Technical Program Chairman: W. W. Kraft, The Lummus Co., 385 Madison Avenue, New York, N. Y.

Chicago, Ill., Palmer House, Sept. 4-6, 1952.

Annual — Cleveland, Ohio, Hotel Cleveland and Carter Hotel, Dec. 7-10, 1952.
Technical Program Chairman: R. L. Savage, Dept. Chem. Eng., Case Inst. of Tech., Univ. Circle, Cleveland 6, Ohio.

SYMPOSIA

Reaction Kinetics
Chairman: B. W. Gamson, Great Lakes Carbon Corp., 333 N. Mich. Blvd., Chicago, Ill.
Meeting—Kansas City, Mo.

Safety in Chemical Plant Operations
Chairman: Matthew M. Braidech, 172 High St., Hastings-on-the Hudson, N. Y.
Meeting—Kansas City, Mo.

Light Hydrocarbon Processing
Chairman: Harold Legatski, 1532 Osage Ave., Bartlesville, Okla.
Meeting—Kansas City, Mo.

The Effect of Company Finances on Engineering Expansion
Chairman: J. R. Riley, Jr., 610 Dwight Bldg., Kansas City, Mo.
Meeting—Kansas City, Mo.

Maintenance
Chairman: D. E. Pierce, General Aniline & Film Corp., 230 Park Ave., New York, N. Y.
Meeting—Rochester, N. Y.

Industrial Applications of Photography
Chairman: Carl Gath, Eastman Kodak Co., Kodak Park Works, Rochester, N. Y.
Meeting—Rochester, N. Y.

Opportunities in Sales for Chemical Engineers
Chairman: L. P. Scoville, Jefferson Chem. Co., 711 Fifth Ave., New York 22, N. Y.
Meeting—Atlantic City, N. J.

Vacuum Engineering
Chairman: W. W. Kraft, The Lummus Co., 385 Madison Avenue, New York, N. Y.
Meeting—French Lick, Ind.

Chemical Engineering Fundamentals
Chairman: W. C. Edmister, Chem. Eng. Dept., Carnegie Inst. of Tech., Pittsburgh 13, Pa.
Meeting—Atlantic City, N. J.

Authors wishing to present papers at a scheduled meeting of the A.I.Ch.E. should first query the Chairman of the A.I.Ch.E. Program Committee, Walter E. Lobo, with a carbon copy of the letter to the Technical Program Chairman of the meeting at which the author wishes to present the paper. Another carbon should go to the Editor, F. J. Van Antwerpen, 120 East 41st Street, New York 17, N. Y. If the paper is suitable for a symposium, a carbon of the letter should go to the Chairman of the Symposia, instead of the Chairman of the Technical Program, since symposia are not scheduled for any meeting until they are complete and approved by the national Program Committee. Before authors begin their manuscripts they should obtain from the meeting Chairman a copy of the Guide to Authors, and a copy of the Guide to Speakers. The first book covers the preparation of manuscripts, and the second covers the proper presentation of papers at A.I.Ch.E. meetings. Presentations of papers are judged at every meeting and an award is made to the speaker who delivers his paper in the best manner. Winners are announced in *Chemical Engineering Progress*, and a scroll is presented to the winning author at a meeting of his local section. Since five copies of the manuscript must be prepared, one should be sent to the Chairman of the symposium and one to the Technical Program Chairman of the meeting, or two to the Technical Program Chairman if no symposium is involved and the other three copies should be sent to the Editor's office. Manuscripts not received 70 days before a meeting cannot be considered.

SYMPOSIUM—ION EXCHANGE

A symposium on "The Industrial Application of Ion Exchange" will be held at the Mellon Institute, Pittsburgh, Pa., April 20, 1951. Sponsors of this one-day meeting are the Akron, Central Ohio, Cleveland, Ohio Valley, Toledo, and Pittsburgh sections of A.I.Ch.E. General chairman and co-chairman, respectively are R. S. Rhodes and A. J. Abrams, both of Koppers Co., Inc., Pittsburgh.

Seven papers are scheduled for the morning and afternoon sessions, highlighting historical and technical developments in ion exchange, and describing specific industrial applications.

The history of ion exchange will be traced by O. M. Elliott, Sun Oil Co., Toledo, and another paper will describe the development of ion-exchange resins. Robert Kunin, Rohm and Haas, Philadelphia, will review recent developments in the industrial application of ion exchange. Two papers will detail specific industrial applications, including a discussion by F. K. Lindsay, National Aluminate Co., Pittsburgh, on the precise conditioning of boiler feed water; the purification of organic chemicals will be described by A. E. Reents, Illinois Water Treatment Co., Rockford, Ill. Domestic applications of ion exchange include a paper by H. E. Otting, M. and R. Dietetic Laboratories, Columbus, Ohio, on the manufacture of special milk products, and a speaker from the Culligan Co., Pittsburgh, will discuss domestic water-softening problems.

Registration for the meeting will take place April 20 at Mellon Institute; premeeting application information is available from James R. West, Mellon Institute, 4400 Fifth Avenue, Pittsburgh 13, Pa. Registration is $2.00 per person and the luncheon fee is $2.50. Hotel reservations may be made with Hotel Webster Hall, Pittsburgh.

Reported by H. L. Kellner

NEW JERSEY

The fifth meeting of the 1950-51 season was held at the Standard Oil Development Co., auditorium in Linden, N. J., with approximately 200 present.

Thomas Chilton, President of A.I.Ch.E., and technical director, development engineering division, engineering department, Du Pont Co., presented a Certificate of Merit awarded to A. E. Lindroos who had received honorable mention at the Minneapolis meeting of the Institute for his presentation of the paper, "Phase Equilibria in the System Nitrogen-Ammonia at High Pressures." Dr. Chilton then spoke to the section on "Units—Scientific and Technical."

Reported by E. P. Foster

DETROIT JUNIOR GROUP

At this group's regular monthly meeting held Feb. 7 in the Junior Room of the Rackham Memorial, W. L. Badger, consulting chemical engineer, W. L. Badger & Co., gave a talk entitled, "Recent Developments in Evaporators." According to Mr. Badger, evaporator design has now been reduced to three general types. They are:

1. Vertical short-tube immersed evaporators
2. Long-tube natural-circulation evaporators
3. Forced-circulation evaporators.

The old caustic pot is on its way out, he said, but added that in the future caustic finishing will be by continuous processes, such as the Dowtherm installation. The most promising of the recent developments, he stated, are the Rosenblad and the Sextuple-effect systems both developed in Sweden to concentrate sulfite waste liquor.

Reported by W. W. Jones

CHEMICAL ENGINEERS CLUB OF WASHINGTON

The meeting on Jan. 29 featured a talk by Thomas P. Forbath of the Chemical Construction Co. on "New Methods of Sulfur Recovery." About 70 members and guests attended. Dr. Forbath pointed out that our supply of pure sulfur will last only 12 to 15 years. He described a new process for recovering high purity sulfur from sulfur-containing minerals. Key to the new process is a gangue separator in which molten sulfur is separated from other materials.

Reported by D. P. Herron

KANSAS CITY

The annual election of officers for this section was held at the Cross Roads Inn, Jan. 24. They are as follows:

Chairman...............S. A. Miller
Chairman-elect.........H. H. Young
Secretary............P. R. Duckworth
Treasurer.............K. L. Pearson
Executive Committee....Fred Kurata
                   and I. E. Miller

Following the election an informal discussion was carried on regarding the plans for the May, 1951, meeting to be held in Kansas City.

Reported by I. E. Miller

EAST TENNESSEE

The 28th general meeting of this section was held Feb. 6 at the Tennessee Eastman Co., Kingsport, Tenn. Approximately 45 members and guests were present. Harold Crouch, process safety engineer, Eastman Kodak Co., Rochester, N. Y., discussed the subject, "Process Safety in the Control of Hazardous Solvents." The general principles, advantages, and disadvantages of thermal conductivity cells, combustion instruments, infrared and ultraviolet absorption and colorimetric methods were discussed as various methods available for determination of solvent vapor concentrations in air.

Reported by J. K. Pannill

NORTHERN CALIFORNIA

This section held its regular monthly meeting at the Engineers' Club in San Francisco Feb. 5. Announced as officers for 1951 were R. W. Lundeen, *chairman*; H. D. Guthrie, *vice-chairman*; and C. R. Wilke, *secretary-treasurer*.

Following the dinner Ascher Opler, Dow Chemical Co., Pittsburg, Calif., addressed the group on the subject "Chemical Engineering Application of Computing Machines." The speaker, project leader in charge of the physics laboratory in the research laboratory at Pittsburg, concentrated his discussion on digital equipment. He described the applications of punch-card machines. Use of the machines in greatly shortening the time for making multicomponent fractionation calculations, and a discussion of their value in rapidly reproducing original compilations of data, were illustrated by slides.

Reported by J. V. Hightower

EL DORADO CHEMICAL ENGINEERS CLUB

The first meeting of the Club for 1951 was held Jan. 18 at the Garrett Hotel in El Dorado, Ark. Donald B. Keyes, A.C.S. tourist speaker, addressed a joint dinner meeting of the South Arkansas Section of A.C.S. and the El Dorado Chemical Engineers' Club on the subject, "Factors Involved in the Appraisal of a Chemical Development." Dr. Keyes is presently a vice-president of Hayden Chemical Corp. Dr. Keyes mentioned three important factors that must be considered in the production of a new development. They are: production cost from test tube to finished product; probable profit, which, according to Dr. Keyes is especially hard to determine; and the length of life of the venture in regard to the turnover of money.

Reported by R. L. Alexander

PITTSBURGH

The annual "Student Night," sponsored by this section, was held at Mellon Institute auditorium Feb. 16. Senior chemical engineering students from Pittsburgh district colleges and universities, including delegations from Penn State College and West Virginia University, were the invited guests and heard Carleton C. Long, St. Joseph Lead Co., Monaca, Pa., discuss "Chemical Engineering Employment." Dr. Long outlined the diverse fields and types of employers confronting the young graduate, and then concluded, "the job is what the engineer makes it."

The talk given by J. W. Raynolds, assistant manager of the chemicals division of General Electric's chemical department before this section on silicones was covered quite adequately in the Journal of Commerce for Feb. 2, 1951.

Reported by Hugh L. Kellner

LOCAL SECTION CALENDAR

SECRETARY'S REPORT

Commission. This appropriation was voted. There was considerable discussion of the activities of the E.J.C. Engineering Manpower Commission and it was felt that the Institute should continue to participate fully in its activities.

An appropriation of $164 was approved as the Institute's share of the estimated operating expenses of the Water Resources Policy Panel of E.J.C. which is continuing its work in this particular field cooperating with the President's Commission in studying the National Water Policy.

P.D.V. Manning was appointed as the liaison member of Council to the Professional Guidance Committee.

PEOPLE

Joseph C. Elgin has been appointed associate dean of the School of Engineering at Princeton (N.J.) University. He will assist Dean Condit in administering the increased activities of the School. Professor Elgin, chairman of the department of chemical engineering for 15 years, is now on sabbatical leave. He will resume his duties as chairman and as associate dean in the fall.

In addition to his other duties, he is a consultant for the Atomic Energy Commission and a trustee of Associated Universities, Inc., which operates Brookhaven National Laboratory at Upton, L. I., for the A.E.C. He also holds consulting positions with industry in the fields of plastics, rubber, and chemicals.

During World War II he served the National Defense Research Committee, War Production Board, and the Manhattan Project, Columbia University.

A member of several professional societies, Professor Elgin is the author of numerous papers and articles in scientific and technical journals. He also holds several patents.

Professor Elgin received his Ph.D. degree from Princeton in 1929 and joined the faculty there the following fall. He became an associate professor in 1935, chairman of the department the following year, and was promoted to a professorship in 1939.

Paul W. Bachman was recently appointed director of research and development of The Davison Chemical Corp., Baltimore, Md., as part of an expanded research program. An announcement to this effect was made by M. G. Geiger, formerly associated with Westvaco Chlorine Products Corp., South Charleston, W. Va., and since early last year executive vice-president of the Davison Chemical Corp. He also is a member of A.I.Ch.E. Dr. Bachman, a graduate of The Johns Hopkins University, has been with the company since 1949, joining Davison as manager of development planning after a service period with the Commercial Solvents Corp.

Forrest O. Calhoon has been named president of the Disco Co., a division of Pittsburgh Consolidation Coal Co., and also assistant vice-president of the parent company. Mr. Calhoon went to Disco early in 1948 after more than 20 years' experience in the manufacture of tar products and industrial chemicals. His first position with Disco was assistant to the president, and he was advanced to vice-president in 1950. Active in several professional associations, Mr. Calhoon is vice-chairman of the Pittsburgh Section of A.I.Ch.E.

NANTZ, VITTONE NOW AT INSTITUTE PLANT

Two members of A.I.Ch.E. are included among recent appointments at the government synthetic rubber plant at Institute, W. Va., operated by the B. F. Goodrich Chemical Co.

Tom B. Nantz, former Hycar production manager at the company's Geon plant at Louisville, Ky., has been named plant manager and will be responsible for the operation of the 90,000 long-ton capacity plant. A graduate of the University of Kentucky, Mr. Nantz has been with Goodrich since 1937. During World War II he served as manager of technical service at the Lone Star Defense Corp. ordnance plant at Texarkana, Tex., which was operated by Goodrich for the government. Since 1943 Mr. Nantz has held various technical and production supervisory positions in *Gr-S* and Hycar American rubber manufacture at the Louisville *Gr-S* and Geon plants. He served as general foreman at the Louisville *Gr-S* plant until 1945 and then became production manager of Hycar American rubbers at the Geon plant. Reference to Mr. Nantz was made in a news account in the January issue of "C.E.P." page 28.

Anton Vittone, former production manager of vinyl materials at Goodrich's Louisville plant, is now production manager at Institute. A graduate of the University of Washington, Mr. Vittone joined Goodrich in 1942 after several years with the Wyandotte Chemicals Corp. Since 1942 he has held various supervisory jobs in the manufacture of *Gr-S*, Hycar American rubber, and Geon polyvinyl chloride. In 1949 he was sent to England on special assignment to British Geon Ltd., an affiliate of B. F. Goodrich.

Joe B. Holmes has been named supervisor of manufacturing of the new West Coast organization of the chemical department of the General Electric Co. He will maintain offices at the chemical department's plant in Anaheim, Calif., which manufactures G - E Glyptal alkyd resins used in paints. A graduate of the University of Missouri with a B.S. in engineering, Mr. Holmes went to General Electric in 1939 as a chemical engineer. Subsequently he became a chemical engineering group leader in charge of process development and design for synthetic organic chemicals and resins and still later section head of the engineering division with responsibility for chemical process development.

Earl F. Arnett is now in charge of the Pittsfield (Mass.) chemical process development section of the General Electric Co.'s chemical department. Mr. Arnett first went with the company in April, 1940, as a chemist in the research section of the new products development laboratory. Subsequently he went to the chemical engineering section of the laboratory, became a chemical engineer for the process development section of the engineering division, and supervisor of pilot plant operations for that section. Prior to going to G.E. he worked as chemical engineer for the Three Rivers Oil Refining Co., and the Standard Oil Company of Louisiana.

John A. Scott will head the newly created and staffed petroleum chemicals division recently set up by Sinclair Refining Co. Mr. Scott joined the Sinclair organization in 1934 as a chemical engineer in the research and development department at East Chicago upon graduating from the University of Minnesota with a degree in chemical engineering. In 1944 he was transferred to Sinclair's Corpus Christi refinery, where he worked on the design, construction and initial operation of the alkylation unit. In 1945 he came to New York as assistant to E. W. Isom, vice-president in charge of research and development, a position he held until his present appointment. Initially the new division's efforts will be devoted to specialized petroleum fractions and petrochemicals now manufactured, such as aromatic solvents.

CHANGES IN WILLIAMS' EMERYVILLE PLANT

Bruce E. McNay, production manager at C. K. Williams & Co., Emeryville (Calif.), plant is leaving that locale to assume new duties and responsibilities in the company's organization at the East St. Louis (Ill.) plant. There he will take charge of a development project concerning the company's expansion program.

Eric Ratcliffe, plant superintendent, succeeds Mr. McNay at Emeryville. Mr. Ratcliffe has served in the capacity of plant superintendent for the past five years since his graduation from the University of Washington where he took his degree in chemical engineering.

Walter A. Myrick, III, formerly assistant manager of the Plains Builders Supply Co., Lubbock, Tex., is now senior chemical engineer, Sinclair Rubber, Inc., Houston, Tex.

Robert Alldredge is now in charge of a new district sales office of the Patterson Foundry & Machine Co., located in Denver, Col. This office has been established to provide faster, specialized service to the chemical processing industries in Colorado, Utah, New Mexico, and Wyoming. Mr. Alldredge was formerly professor of engineering, Alldredge & Horbit.

L. G. Bortolin is now in the employ of Dominion Rubber Co., Ltd., as a development engineer. He had previously been associated with Canadian Celanese Ltd.

E. E. Kimmel has been appointed technical adviser for the chemical division of Koppers Co., Inc. In his new position he will be responsible for coordination of all technical matters relating to the development, sale, and use of products presently produced or contemplated for production by Koppers chemical division. Before joining Koppers as assistant to the technical adviser for the chemical division in 1949, Mr. Kimmel was manager of the research laboratory for coal chemicals and synthetic resins of the Interlake Chemical Corp. He received a B.S. in chemical engineering from Ohio State University. Subsequently he joined the Carnegie-Illinois Steel Corp. as a research chemist in coal chemicals at Clairton, Pa., and from 1942-45 was a research engineer with the Battelle Memorial Institute, Columbus, Ohio.

CLASSIFIED SECTION

Advertisements in the Classified Section of Chemical Engineering Progress are payable in advance, and are placed at 15c a word, with a minimum of four lines accepted. Box number counts as two words. Advertisements average about six words a line. Members of the American Institute of Chemical Engineers in good standing are allowed one six-line insertion free of charge per year. More than one insertion to members will be made at half rates. In using the Classified Section of Chemical Engineering Progress it is agreed by prospective employers and employees that all communications will be acknowledged, and the service is made available on that condition. Boxed advertisements one-inch deep are available at $15 an insertion. Size of type may be specified by advertiser. In answering advertisements all box numbers should be addressed care of Chemical Engineering Progress, Classified Section, 120 East 41st Street, New York 17, N. Y. Telephone ORegon 9-1560. Advertisements for this section should be in the editorial offices the 20th of the month preceding the issue in which it is to appear.

SITUATIONS OPEN

CHEMICAL ENGINEER

Large Western New York synthetic organic chemical plant, noted for its high-quality manufacturing standards, has attractive permanent position for chemical engineer with 2 to 3 years' industrial experience on plant engineering projects. Liberal starting salary, with periodic review of performance for salary increases. Excellent working conditions, cafeteria, pension plan, plus group life, sickness and accident insurance. Reply in confidence to: Superintendent of Personnel Relations, Box 1-3.

Wanted—Associate or full professor of Petroleum Production Engineering in a leading institution. Must have successful professional and research background. Prefer man qualified in phase relationships of oil and gas mixtures, petroleum reservoir engineering and design. Work to begin September fifteenth. Box 2-3.

Head of Classifying and Filing Section in Technical Information Division of Research Laboratory.—Position will require ability, training, and preferably experience in chemical engineering or chemistry, plus training or experience in technical filing. Work will involve planning and supervisory aspects and coordination of departmental filing systems and files. Give experience, education, and salary desired. Ethyl Corporation, 1600 W. 8 Mile Rd., Ferndale 20, Detroit, Michigan.

Chemical Engineers—to do process research, must be graduate of recognized engineering college with some experience, married and 25 to 40 years old. Florida industry. Give full information with salary expected in first letter. Address all correspondence to P.O. Box 3269, Tampa 1, Florida.

Wanted—Chief chemist for laboratory in Midwest location who conducts chemical and physical tests on rubber. Must be an alert, aggressive good manager. State full details on education, experience and salary requirements. Box 12-3.

WHO AND WHAT!

NOTE: POSITION SEEKERS
Who's wanted...What's offered...

NOTE: EMPLOYERS
Who's available...What's the experience...

You as an employer or potential employee owe it to yourself to investigate the monthly pages of Chemical Engineering Progress. Either step into a better position offering challenging opportunities—or build, enlarge or expand your staff with the best in the field—with the help of Chemical Engineering Progress.

SITUATIONS WANTED

A.I.Ch.E. Members

Chemical Engineer—M.S. Certified professional engineer. Eleven years' diversified experience in design, development, process improvement and maintenance. Desire responsible position as senior engineer. Box 3-3.

Chemical Engineer—Construction—B.S.Ch.E. (48) Pilot plant design and development inorganic chemical plant design, layout, specification writing, project planning. Field experience: equipment inspection, pile footings. Desire position as an executive assistant. Available immediately. Box 4-3.

Plastics Chemical Engineer—Ph.D. Outstanding twenty-year career in invention, development and supervision of manufacture of synthetic resins, molding compounds and paper additives. Wish to relocate as head of or advisor on development, market analysis, negotiator, or similar position. Will travel. Languages; writing and speaking ability. Aggressive and congenial personality. Moderate salary requirement. Consulting connection acceptable. Box 5-3.

Ph.D. Candidate—In chemical engineering with industrial management minor desires summer employment. Opportunity for mutual observation prior to permanent employment. Three years graduate work, B.Ch.E., M.S., scholarships, honor and professional societies. Wilmington-Philadelphia area preferred. Draft exempt. Age 24. Box 6-3.

Project Engineer—B.S.Ch.E., age 32. Nine years' diversified experience in chemical plant operations and design and oil refinery design. Desire responsible supervisory position with aggressive company. Will accept either domestic or foreign assignment. Box 7-3.

Chemical Engineer—M.S., Ph.D. (U. S. A.) Single, 29, Indian citizen. Experience in teaching, pilot plant supervision, economic evaluation. Desire long term university/industrial research or development. Box 8-3.

Chemical Engineer—Columbia, Ph.D., 1948; Tau Beta Pi, Sigma Xi, Phi Lambda Upsilon. Experience in research and development since graduation. Desire position requiring imagination, initiative, resourcefulness and leadership. Any location. Box 9-3.

Sales Engineer—B.S.Ch.E., 1942. Age 32, married, one child. Eight years' process and sales experience. No military service. Desire to represent progressive equipment or instrument manufacturer. Box 10-3.

Chemical Engineer—M.S., U. of Mich. Age 27, veteran, family. Three years process development in synthetic organics. Desire development or production position with oil or chemical company west of Mississippi. Box 11-3.

Walter A. Schmidt, president and general manager of the Western Precipitation Co., Los Angeles, has been re-elected a director-at-large of the American Chemical Society for a four-year term. Mr. Schmidt served as an engineer on the staff of the Western Precipitation Co. from 1908-11. Subsequently he became president and general manager. He also is president of the Precipitation Company of Canada, Ltd., Montreal, and the International Precipitation Co., and is an officer and director of the Westwell Chemical Co., Whittier, Calif.

Herbert W. Yeagley, who has been serving as Washington representative of the Monsanto Chemical Co., since 1949, has been granted a leave of absence to attend the advanced management course at Harvard University Graduate School of Business Administration. After completing his studies, he will be assigned to the company's organic chemicals division at St. Louis. Mr. Yeagley has been with Monsanto since 1942, when he joined the John F. Queeny plant as control chemist. He later became research engineer and assistant furnace supervisor in the phosphate division prior to joining the Washington staff.

Luis H. Bartlett, formerly with the Engineering Experiment Station of the Louisiana State University, Baton Rouge, La., is now with the department of chemical engineering at Oklahoma A. & M. College, Stillwater, Okla.

E. H. Smoker has been appointed operating manager and **W. D. McElroy,** gas engineer, in the United Gas Improvement Co.'s operating department headquarters staff in Philadelphia, Pa.

Cyrus W. Richardson has recently become associated with the Northwest Lead Co., Seattle, Wash., as metallurgist. He was formerly plant superintendent with Manganese Products, Inc., in the same city.

W. E. Fremgen, previously employed by Carthage Hydrocol at Brownsville, Tex., has returned as a process engineer with the Lago Oil & Transport Co., Ltd., Aruba, Netherlands, West Indies.

E. W. O'Keefe, formerly with Charles F. Pfizer & Co., has joined the technical department of the Niagara Falls Geon plant of the B. F. Goodrich Chemical Co. He will work on development of process improvements.

James F. Culverwell is now employed as an engineer in the engineering department of the Du Pont Co., at Wilmington, Del. Previously he was a graduate student at Northwestern University, Evanston, Ill., and prior to that a graduate assistant at Pennsylvania State College, State College.

D. F. SMITH WITH DAVIS & GECK, INC.

David F. Smith recently joined Davis & Geck Inc., a subsidiary of American Cyanamid Co., as director of development. He will have the responsibility for the development of new products.

He has recently been director of research, development and control and member of the board of directors of Johnson and Johnson and director and vice-president of the Research Foundation. He is the author of 33 published scientific papers and patents.

Dr. Smith was born in Springdale, Conn., and was educated at California Institute of Technology where he received the Ph.D. degree in physical chemistry and physics.

J. Paul Ekberg, Jr., has been appointed to fill the newly created post of assistant manager of petroleum chemicals sales of Monsanto Chemical Co.'s organic chemicals division. Mr. Ekberg has been with Monsanto since 1940 when he was graduated from Yale University with a B.E. degree in chemical engineering. He was employed as an analytical chemist and production supervisor prior to entering petroleum chemicals sales in 1946.

William P. Bebbington, formerly with the planning division of the polychemicals department, has been transferred to the atomic energy division of the explosives department of the Du Pont Co. He is serving in the capacity of chemical engineer at Wilmington, Del.

E. F. Wagner is now director of the technical service of the Chicago office of the Witco Chemical Co. Previously he was director of research. The company is broadening its technical service department to provide industry with more information on critical materials and substitutes in order to help offset shortages that lie ahead in its field.

J. S. Chowning, formerly with the Lapp Insulator Co., LeRoy, N. Y., is now employed by the Corning Glass Works, Corning, N. Y. His title is manager of the plant equipment sales department.

James R. Gaskill has severed his connection with the Avoset Co., Gustine, Calif., which he served as research and development engineer. He is now with the California Research and Development Co. as chemical engineer.

Robert J. Keating, formerly purchasing agent of Orchard Bros., Inc., is now secretary-treasurer of the company.

John T. Hegeman was recently advanced from plant chemist to assistant kraft superintendent with the Brown Co., Berlin, N. H.